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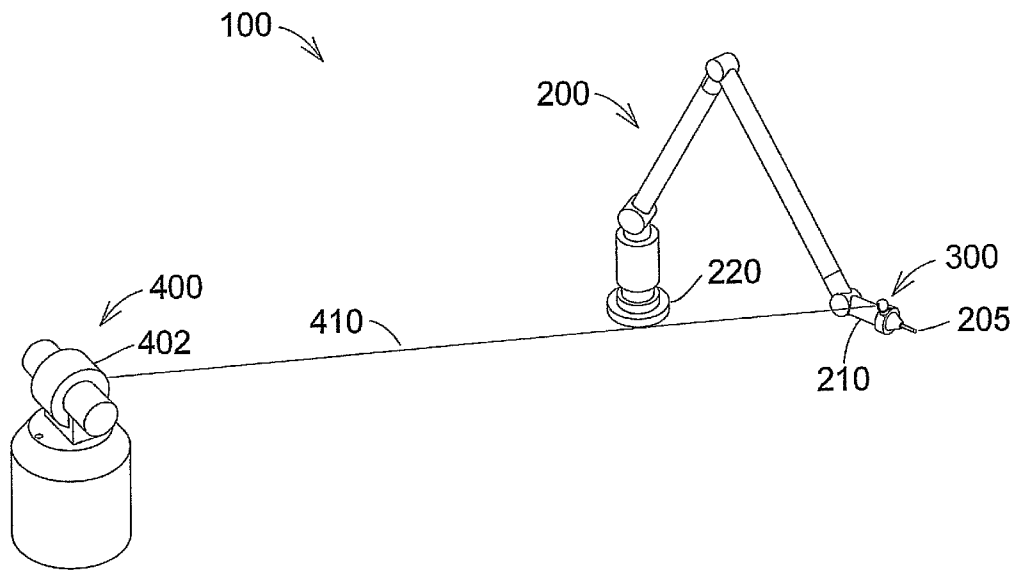
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(57) Abstract: A measurement apparatus, system and method for measuring objects which is easily relocatable about the object is described. The system uses an articulated-arm coordinate measuring machine (CMM) (200) and a laser tracker (400). A retroreflector (310, 312) for use with the laser tracker is located on the arm of the articulated-arm (CMM). A common coordinate frame of reference can be determined for the CMM and the laser tracker so that the CMM can be moved. Also, points hidden from the laser tracker can be measured for example with the CMM.

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## **APPARATUS AND METHOD FOR RELOCATING AN ARTICULATING-ARM COORDINATE MEASURING MACHINE**

### **CROSS-REFERENCE**

[0001] This application claims priority to U.S. provisional application 60/693,295 filed June 23, 2005, which is incorporated herein by reference.

### **BACKGROUND**

[0002] The present disclosure relates to two coordinate measuring devices. One of these devices belongs to a class of instruments that measure the coordinates of a point by probing the point with an articulated mechanical structure. The probing may be performed with a mechanical probe tip or with a non-contact scanning device. The position of the probe tip is determined by the readings of angular encoders located at the mechanical joints that interconnect the articulating segments. This type of device, whether it uses a mechanical probe tip or a scanner, is referred to as an articulated-arm coordinate measuring machine (CMM). An exemplary system belonging to this class of devices is described by U.S. Patent No. 5,402,582 to Raab.

[0003] The other of these devices is an instrument, referred to as a laser tracker, which measures the coordinates of a point by sending a laser beam to a retroreflector target that is in contact with the point. The laser tracker determines the coordinates of the point by measuring the distance and the two angles to the retroreflector. The distance is measured with a distance-measuring device such as an absolute distance meter or an interferometer. The angles are measured with an angle-measuring device such as an angular encoder. A gimbaled beam-steering mechanism within the instrument directs the laser beam to the point of interest. Exemplary systems belonging to this class of instruments are described by U.S. Patent No. 4,790,651 to Brown et al. and U. S. Patent No. 4,714,339 to Lau et al.

[0004] The articulated-arm CMM is capable of being bent into a variety of orientations. Because of this, it is able to measure "hidden" points; that is, points that are hidden from the line-of-sight view of a measuring device such as a laser tracker. On the other

hand, the laser tracker can measure over a much larger volume than the articulated-arm CMM. What is needed is a way to obtain the convenience of measuring hidden points with the articulated-arm CMM over the larger measurement volume of the laser tracker.

## SUMMARY

[0005] An embodiment may comprise a system for coordinate measurement comprising: a laser tracker; a retroreflector; a moveable articulated-arm coordinate measuring machine (CMM) that may be relocated to different positions; an assembly for attaching the retroreflector to the articulated-arm coordinate measuring machine (CMM); wherein the system is structured so that a laser beam may be sent from the laser tracker in order to measure a position of the retroreflector relative to the laser tracker in a first coordinate system while the articulated-arm coordinate measuring machine (CMM) also measures the position of retroreflector relative to the articulated-arm coordinate measuring machine (CMM) in a second coordinate system and wherein the moveable articulated-arm coordinate measuring machine (CMM) may be relocated to different positions and the measurements may be performed again; and means for transforming the first coordinate system and/or the second coordinate system to a common coordinate frame of reference.

[0006] An embodiment may comprise a method for coordinate measurement comprising: placing a laser tracker at a fixed location; placing at another location a moveable articulated-arm coordinate measuring machine (CMM) to which a retroreflector has been attached thereto so that the retroreflector may be moved to different locations while the laser tracker remains in the fixed location; sending and reflecting a laser beam from the laser tracker to the retroreflector in order to measure a position of the retroreflector in a first coordinate system and also measuring the position of the retroreflector with the articulated-arm coordinate measuring machine (CMM) while the retroreflector is located in the same position in order to also measure the position of the retroreflector relative to the articulated-arm coordinate measuring machine (CMM) in a second coordinate system; and transforming the measurements of the position of the retroreflector taken in first coordinate system and/or the second coordinate system to a common coordinate frame of reference.

[0007] An embodiment may also comprise a retroreflector assembly for use with an articulated-arm coordinate measuring machine (CMM) comprising: a retroreflector; and a mount to attach the retroreflector on the articulated-arm coordinate measuring machine (CMM).

[0008] An embodiment may also comprise a method of relocating an articulated-arm coordinate measuring machine (CMM) for measuring an object at different positions about the object comprising: measuring a first set of coordinates in a first coordinate system of a first position of a retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM); measuring also a first set of second coordinates in a second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker; moving links of the articulated-arm coordinate measuring machine (CMM) to reposition the retroreflector to a second position and measuring a second set of coordinates in a first coordinate system of the second position of the retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM); measuring also a second set of second coordinates in the second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker; moving the links of the articulated-arm coordinate measuring machine (CMM) to reposition the retroreflector to a third position and measuring a third set of coordinates in a first coordinate system of the third position of the retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM); measuring also a third set of second coordinates in a second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker; and forming a transformation matrix with the three sets of first and second coordinates that relates all of the sets of coordinates to a common frame of reference.

[0009] An embodiment may also comprise a laser measurement apparatus for measuring objects comprising: an articulated-arm coordinate measuring machine (CMM) having angular encoders; a laser tracker having a distance meter and angular encoders; and a retroreflector for use with the laser tracker located on the arm of the articulated-arm (CMM).

## **BRIEF DESCRIPTION OF THE DRAWINGS**

[0010] Referring now to the drawings, examples of embodiments are shown which should not be construed to be limiting regarding the entire scope of the disclosure, and wherein the elements are numbered alike in several FIGURES:

[0011] FIGURE 1 is a perspective view of an articulated-arm CMM used in conjunction with a laser tracker;

[0012] FIGURE 2 is an exploded, perspective view of a retroreflector clamp assembly;

[0013] FIGURE 3 is a perspective view of the articulated-arm CMM relocated to a second position through the use of the laser tracker;

[0014] FIGURE 4 is a perspective view of a mounted sphere assembly;

[0015] FIGURES 5A and 5B are perspective views of the retroreflector nest in contact with the mounted sphere; and

[0016] FIGURES 6A and 6B are perspective view of an articulated-arm CMM with reference made to the mathematical nomenclature.

## **DETAILED DESCRIPTION OF EXEMPLARY EMBODIMENT**

[0017] Reference will now be made in detail to an exemplary embodiment, an example of which is illustrated in the accompanying drawing.

[0018] An example of a large-scale coordinate probing system 100 is shown in FIGURE 1. Probing system 100 comprises articulated-arm CMM 200, retroreflector clamp assembly 300, and laser tracker 400. Other orientations, arrangements, set-ups, and variations are possible and contemplated depending upon the specific application in the field for example. Thus, this example should not be considered to be limiting.

[0019] FIGURE 2 shows an exploded view of retroreflector clamp assembly 300, which comprises spherically mounted retroreflector (SMR) 310, kinematic nest 320, and clamp 330. SMR 310 comprises cube-corner retroreflector 312 embedded within partial sphere 314. Cube-corner retroreflector 312 comprises three flat mirror segments (M1, M2, M3) which are joined together in such a way that each glass segment makes a ninety degree angle with respect to the other two glass segments. The point of common intersection of the three glass segments is called the apex "A" of SMR 310. The apex "A" is located at the spherical center of partial sphere 314.

[0020] Kinematic nest 320 attaches to the top of clamp 330, which in turn locks onto the final link 210 of articulated-arm CMM 200. Thus, the clamp 330 allows the retroreflector clamp assembly 300 to be placed onto articulated-arm CMM 200.

[0021] Kinematic nest 320 has three point-like contacts (not shown) onto which the spherical surface of SMR 310 rests. These point-like contacts ensure that the center of SMR 310 remains at the same point in space as SMR 310 is rotated. Kinematic nest 320 preferably contains a magnet in its base to ensure that SMR 310 is kept in constant contact with the three point-like contacts.

[0022] As shown in Figure 1, Laser tracker 400 sends laser beam 410 to SMR 310. Cube-corner retroreflector 312 reflects the light from the laser tracker back to the laser tracker 400 along the same line 410 as the outgoing laser beam. The laser tracker 400 monitors the position of the returning laser beam and adjusts the position of the tracker head 402 to keep the laser beam centered on SMR 310, even as the SMR 310 is moved from point to point. In this example, the operator moves the end of articulated-arm CMM 200 to three distinct positions, but may also move the articulated-arm CMM 200 to twelve or more positions or possibly one position only. At each position, measurements of the SMR 310

retroreflector coordinates are made by both articulated-arm CMM 200 and laser tracker 400. Articulated-arm CMM 200 does this by using its built-in angular encoders (not shown) which typically are located in the joints of the articulated-arm CMM 200. Laser tracker 400 does this by using its distance meter and angular encoders (not shown). Other types of encoders and distance meters may also be used.

[0023] By comparing this data collected by articulated-arm CMM 200 and laser tracker 400, a transformation matrix is determined for converting from the coordinate system of articulated-arm CMM 200 to the coordinate system of laser tracker 400 or vice versa. Alternatively, both sets of data can be converted into some other preferred coordinate system *xyz*.

[0024] When measuring a large object with articulated-arm CMM 200, it is often necessary to move articulated-arm CMM 200 to a different position in order to measure other portions of the large object that are not accessible to measurement from the first position. This action of moving articulated-arm CMM 200 to a different position is referred to as "relocation." The above procedure of simultaneously measuring the position of SMR 310 with articulated-arm CMM 200 and laser tracker 400 is performed whenever articulated-arm CMM 200 is relocated (see Figure 3 where articulated-arm CMM 200 is moved from position A to position B for example). This permits the data collected from the several locations of articulated-arm CMM 200 to be seamlessly stitched together in the same common coordinate system in the same frame of reference. With the method described above, articulated-arm CMM 200 can be quickly and accurately relocated to any position within the measurement volume of laser tracker 400.

[0025] This is a great improvement over prior art solutions where such an relatively easy relocation process is not possible because several nests (for example four nests) were usually placed on a floor as a frame of reference for an articulated-arm CMM. Thus, the nests had to also be relocated when an articulated-arm CMM was relocated and all points of reference had to be relatively recalibrated for example.

[0026] An example of articulated-arm CMM 200 moved from a first position (POSITION A) to a second position (POSITION B) to measure a large object 600 is shown in

FIGURE 3. In this figure, the laser tracker 400 provides fast and accurate relocation of the articulated-arm CMM 200.

[0027] The following techniques may also be implemented to improve the accuracy of relocating an articulated-arm CMM: (1) measure many points (for example, more than three) with the articulated-arm CMM and laser tracker; (2) measure points separated as much as possible in three-dimensional space (that is, near the outer edges of the articulated-arm measurement envelope); and (3) measure points covering all three dimensions (that is, avoid collecting points that lie entirely on or near a plane).

### **COMPENSATION TO FIND SMR POSITION**

[0028] When retroreflector clamp assembly 300 is first attached to articulated-arm CMM 200, the coordinates of SMR 310 must be found in relation to the frame of reference of final link 210 (see Fig. 6B). To do this, a compensation procedure is performed using mounted sphere 500 shown in Fig. 4. This may also be termed an "initial compensation" procedure, because it is only necessary to be performed when the retroreflector clamp assembly 300 is first attached to articulated-arm CMM 200.

[0029] Mounted sphere 500 comprises metal sphere 510, magnetic nest 520, and base 530. Metal sphere 510 may have the same diameter as SMR 310, for example. Magnetic nest 520 has three point-like contacts (not shown) onto which the metal sphere 510 rests. A magnet (not shown) holds metal sphere 510 securely against the three point-like contacts. Magnetic nest 520 is attached to base 530, which in turn is attached to the floor on another stable surface.

[0030] At the start of the compensation procedure to find the SMR position, SMR 310 is removed from kinematic nest 320. Kinematic nest 320 is brought in contact with metal sphere 510, which is sitting on magnetic nest 520. This is shown in FIGURE 5A. Subsequently, the links or sections of articulated-arm CMM 200 are moved into a different position, as shown in FIGURE 5B. The exact position of kinematic nest 320 is not important. By repositioning the links at least one more time, but preferably many more times, the angles

on the angular encoders of articulated-arm CMM can be used to determine the position of the center of SMR 310.

[0031] The mathematics for determining coordinates using articulated links such as are found on robots or articulated-arm CMMs are well known. For example, the relevant equations are described in chapters 3 and 4 of Robot Modeling and Kinematics by Rachid Manseur. With these equations, one can relate the position  $\vec{r}'$  of the center of metal sphere 510 within the frame of reference of final link 210 to the position  $\vec{r}$  of the center of metal sphere 510 within the fixed frame of reference of base 220 of articulated-arm CMM 200. Possible vectors  $\vec{r}'$  and  $\vec{r}$  for a particular articulated arm CMM are shown in FIGURES 6A, 6B. To clarify the meaning of these vectors, local coordinate systems  $(x_A, y_A, z_A)$  and  $(x_F, y_F, z_F)$  for articulated-arm CMM 200 and final link 210, respectively, are shown in FIGURES 6A, 6B. In the case of the compensation procedure to find the coordinates of the SMR as described above, the constraint of metal sphere 510 causes vectors  $\vec{r}'$  and  $\vec{r}$  to remain constant even as the links of articulated-arm CMM 200 are moved about. The equation that relates the two vectors is:

$$\vec{r} = T(\vec{\theta}_i) \cdot \vec{r}' . \quad (1)$$

[0032] In this equation,  $T(\vec{\theta}_i)$  is a 4 x 4 transformation matrix that depends on the so-called Denavit-Hartenberg (DH) parameters for each link, as explained in the book by Manseur cited above. For each link, only one of DH parameters, the link angle  $\theta$ , varies during the compensation procedure. The other DH parameters are characteristic of a particular articulated-arm CMM and will already have been determined by a factory compensation procedure carried out at the time the articulated-arm CMM is manufactured. The fixed parameters are determined by a separate factory compensation procedure. The vector notation  $\vec{\theta}_i$  indicates that  $T$  is a function of the angular encoder readings for all of the joints in the Arm, and  $i$  indicates the  $i^{\text{th}}$  measurement, where each measurement corresponds to a different position of articulated-arm CMM 200, two example positions of which are shown in FIGURES 5A, 5B. If articulated-arm CMM 200 is moved to a large number of different positions, there will not be a unique solution to Equation (1). Instead, the best

estimate of the vectors  $\bar{r}'$  and  $\bar{r}$  is made by minimizing the total residual error. For the  $i^{\text{th}}$  measurement, the residual error is defined as:

$$res_i = |T(\bar{\theta}_i) \cdot \bar{r}' - \bar{r}|. \quad (2)$$

To minimize the total residual error,  $\bar{r}'$  and  $\bar{r}$  are selected to minimize the sum of the square of the  $res_i$  values. In this case,  $\bar{r}'$  and  $\bar{r}$  are each represented by three coordinate values (for example,  $x$ ,  $y$ , and  $z$ ), so that there are six parameter values that need to be found. The procedure for selecting parameters to minimize a sum of squared values is well known in the art and is readily carried out using widely available software. This procedure will therefore not be discussed further.

## RELOCATION CALCULATION

[0033] As mentioned previously, articulated-arm CMM 200 is conveniently relocated by simultaneously measuring by position of SMR 310 with articulated-arm CMM 200 and laser tracker 400 with SMR 310 moved to several different positions. The measurements collected by articulated-arm CMM 200 are related to the measurements of laser tracker 400 through the equation:

$$\bar{s} = M(rx, ry, rz, tx, ty, tz) \cdot \bar{s}'. \quad (3)$$

[0034] In this equation,  $\bar{s}$  and  $\bar{s}'$  are the coordinates of the SMR 310 in the frame of reference of laser tracker 400 and the frame of reference of articulated-arm CMM 200, respectively. The quantities  $rx, ry, rz$  are the Euler angles representing rotations about the X, Y and Z axes respectively, and  $tx, ty, tz$  are the displacements in X, Y and Z respectively. The matrix  $M(rx, ry, rz, tx, ty, tz)$  transforms the coordinates of SMR 310, as measured by the relocated articulated-arm CMM 200, into the frame of reference of laser tracker 400 which in this example is the common coordinate frame of reference. However, it possible to use, or assign, any suitable frame of reference to be the common coordinate frame of reference. This matrix  $M(rx, ry, rz, tx, ty, tz)$  is the entity determined by the relocation procedure, and it the matrix may be computed in any suitable means such as in a processor or in software (not

shown) for example. Once it is known, it can equally be applied to a measurement of a probe tip 205 attached to the final link 210. The probe-tip 205 coordinate, as measured by articulated-arm CMM 200, is transformed by matrix  $M(rx, ry, rz, tx, ty, tz)$  to give the coordinates of the probe tip 205 in the frame of reference of laser tracker 400.

[0035] To find  $M(rx, ry, rz, tx, ty, tz)$ , the residual error for the  $i^{th}$  measurement is defined as

$$res_i = |M(rx, ry, rz, tx, ty, tz) \cdot \bar{s}' - \bar{s}|. \quad (4)$$

[0036] A standard least-squares fit calculation is performed to find the values of the 6 fit parameters  $rx, ry, rz, tx, ty, tz$  that minimize the sum of the squares of the residual errors.

[0037] It will be apparent to those skilled in the art that, while an exemplary embodiment has been shown and described, various modifications and variations can be made to the apparatus and method of relocating an articulated-arm CMM by measuring a retroreflector mounted on the articulated-arm CMM with a laser tracker disclosed herein without departing from the spirit or scope of the invention. Accordingly, it is to be understood that the various embodiment has been described by way of illustration and not limitation.

What is claimed is:

1. A system for coordinate measurement comprising:
  - a laser tracker;
  - a retroreflector;
  - a moveable articulated-arm coordinate measuring machine (CMM) that may be relocated to different positions;
  - an assembly for attaching the retroreflector to the articulated-arm coordinate measuring machine (CMM);wherein the system is structured so that a laser beam may be sent from the laser tracker in order to measure a position of the retroreflector relative to the laser tracker in a first coordinate system while the articulated-arm coordinate measuring machine (CMM) also measures the position of retroreflector relative to the articulated-arm coordinate measuring machine (CMM) in a second coordinate system and wherein the moveable articulated-arm coordinate measuring machine (CMM) may be relocated to different positions and the measurements may be performed again; and
  - means for transforming the first coordinate system and/or the second coordinate system to a common coordinate frame of reference.
2. The system of claim 1 wherein:
  - the laser tracker is fixed in place.
3. The system of claim 1 wherein the retroreflector comprises a spherically mounted retroreflector (SMR).
4. The system of claim 1 wherein the retroreflector comprises a cube-corner retroreflector

5. A method for coordinate measurement comprising:
- placing a laser tracker at a fixed location;
  - placing at another location a moveable articulated-arm coordinate measuring machine (CMM) to which a retroreflector has been attached thereto so that the retroreflector may be moved to different locations while the laser tracker remains in the fixed location;
  - sending and reflecting a laser beam from the laser tracker to the retroreflector in order to measure a position of the retroreflector in a first coordinate system and also measuring the position of the retroreflector with the articulated-arm coordinate measuring machine (CMM) while the retroreflector is located in the same position in order to also measure the position of the retroreflector relative to the articulated-arm coordinate measuring machine (CMM) in a second coordinate system; and
  - transforming the measurements of the position of the retroreflector taken in first coordinate system and/or the second coordinate system to a common coordinate frame of reference.
6. The method of claim 5 further comprising:
- moving links of the articulated-arm coordinate measuring machine (CMM) to move the retroreflector to at least two other different positions relative to the laser tracker and taking a set of measurements at each location with both the laser tracker and the articulated-arm coordinate measuring machine (CMM) to result in at least three sets of measurements at least three different positions.
7. The method of claim 6 wherein the transforming the measurements of the position of the retroreflector taken in first coordinate system and/or the second coordinate system to a common coordinate frame of reference is performed using a matrix and the set of measurements taken at the three positions.

8. The method of claim 7 wherein the transforming the measurements of the position of the retroreflector taken in first coordinate system and/or the second coordinate system to a common coordinate frame of reference is performed using a matrix further comprises:

relating the measurements made by the articulated-arm coordinate measuring machine (CMM) to the measurements of the laser tracker through the equation:

$$\bar{s} = M(rx, ry, rz, tx, ty, tz) \cdot \bar{s}' .$$

where:  $\bar{s}$  and  $\bar{s}'$  are the coordinates of the retroreflector in the frame of reference of the laser tracker and the frame of reference the articulated-arm coordinate measuring machine (CMM), respectively,

the quantities  $rx, ry, rz$  are the Euler angles representing rotations about X, Y and Z axes respectively, and

$tx, ty, tz$  are the displacements in X, Y and Z respectively and thus the matrix is:

$$M(rx, ry, rz, tx, ty, tz)$$

and the matrix transforms the coordinates of the retroreflector as measured by the articulated-arm coordinate measuring machine (CMM) into the frame of reference of the laser tracker which is used as the common frame of reference.

9. A retroreflector assembly for use with an articulated-arm coordinate measuring machine (CMM) comprising:

a retroreflector; and

a mount to attach the retroreflector on the articulated-arm coordinate measuring machine (CMM).

10. The retroreflector assembly of claim 9 wherein the retroreflector comprises a spherically mounted retroreflector (SMR).

11. The retroreflector assembly of claim 9 wherein the retroreflector comprises a cube-corner retroreflector

12. A method of relocating an articulated-arm coordinate measuring machine (CMM) for measuring an object at different positions about the object comprising:

measuring a first set of coordinates in a first coordinate system of a first position of a retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM);

measuring also a first set of second coordinates in a second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker;

moving links of the articulated-arm coordinate measuring machine (CMM) to reposition the retroreflector to a second position and measuring a second set of coordinates in a first coordinate system of the second position of the retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM);

measuring also a second set of second coordinates in the second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker;

moving the links of the articulated-arm coordinate measuring machine (CMM) to reposition the retroreflector to a third position and measuring a third set of coordinates in a first coordinate system of the third position of the retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM);

measuring also a third set of second coordinates in a second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker; and

forming a transformation matrix with the three sets of first and second coordinates that relates all of the sets of coordinates to a common frame of reference.

13. The method of claim 12 of relocating an articulated-arm coordinate measuring machine (CMM) for measuring an object at different positions about the object further comprising:  
using the transformation matrix to relate a fourth set of coordinate measurements taken by the articulated-arm coordinate measuring machine (CMM) of hidden positions which are hidden from the laser tracker to the common frame of reference.

14. A laser measurement apparatus for measuring objects comprising:  
an articulated-arm coordinate measuring machine (CMM) having angular encoders;  
a laser tracker having a distance meter and angular encoders; and  
a retroreflector for use with the laser tracker located on the arm of the articulated-arm (CMM) .

15. A method of relocating an articulated-arm coordinate measuring machine (CMM) for measuring an object at different positions about the object comprising:  
measuring a first set of coordinates in a first coordinate system of a first position of a retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM);  
measuring also a first set of second coordinates in a second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker;  
moving links of the articulated-arm coordinate measuring machine (CMM) to reposition the retroreflector to a second position and measuring a second set of coordinates in a first coordinate system of the second position of the retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM);  
measuring also a second set of second coordinates in the second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser

beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker;

moving the links of the articulated-arm coordinate measuring machine (CMM) to reposition the retroreflector to a third position and measuring a third set of coordinates in a first coordinate system of the third position of the retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM);

measuring also a third set of second coordinates in a second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker;

moving the links of the articulated-arm coordinate measuring machine (CMM) to reposition the retroreflector to a fourth position and measuring a fourth set of coordinates in a first coordinate system of the fourth position of the retroreflector located on an arm of an articulated-arm coordinate measuring machine (CMM) by using angular sensors located in the articulated-arm coordinate measuring machine (CMM);

measuring also a fourth set of second coordinates in a second coordinate system of the retroreflector located on the arm by using a laser tracker and a laser beam sent from the laser tracker to reflect back from the retroreflector to the laser tracker; and

forming a transformation matrix with the four sets of first and second coordinates and/or additional sets of fifth, sixth, seventh, or more sets of measured data that relates all of the measured sets of coordinates to a common frame of reference.

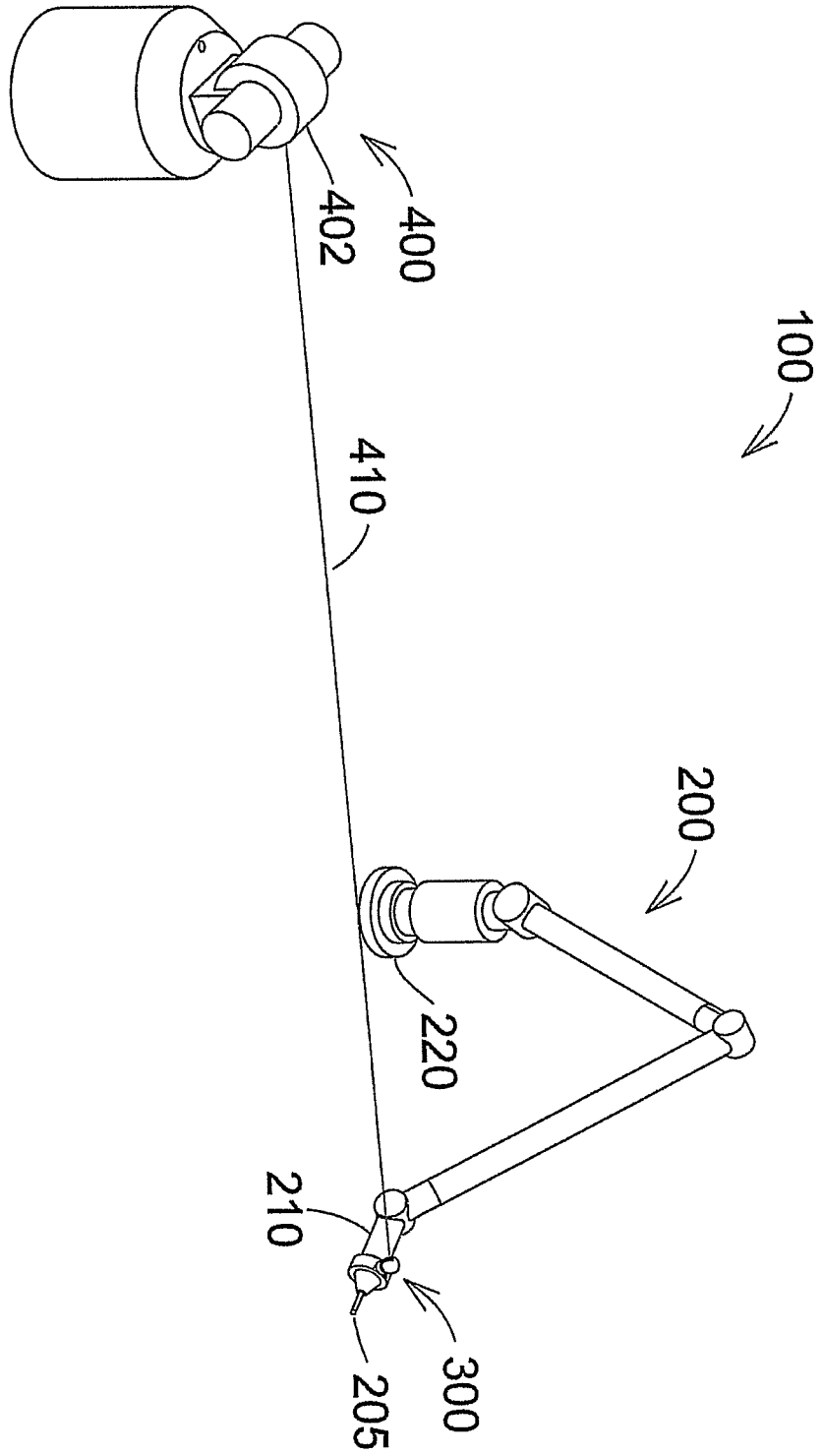


FIGURE 1

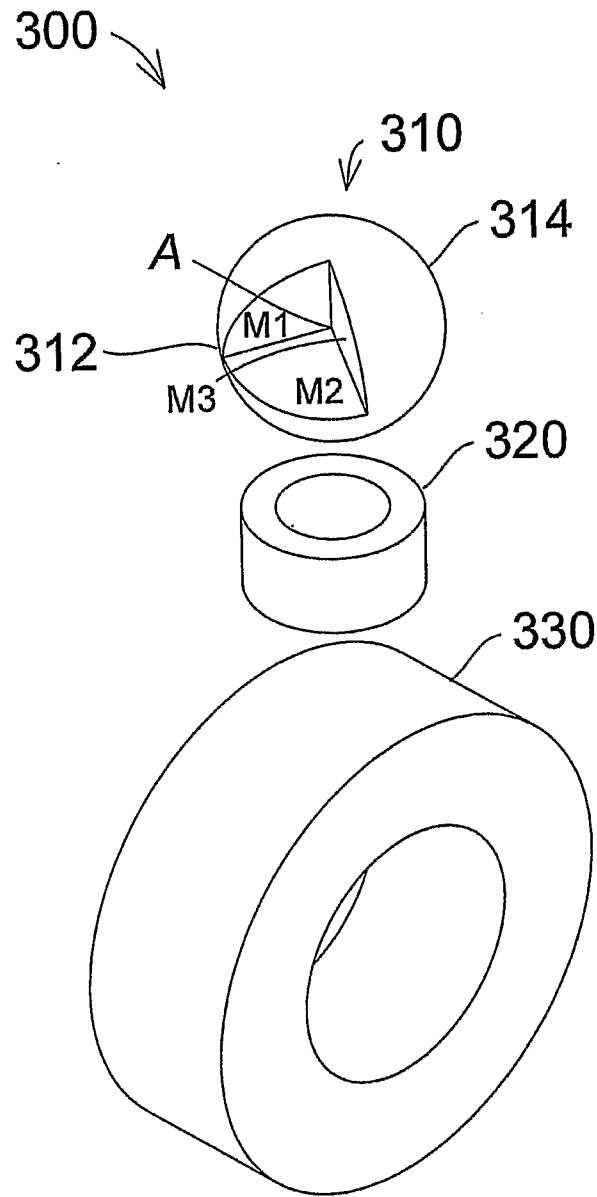


FIGURE 2

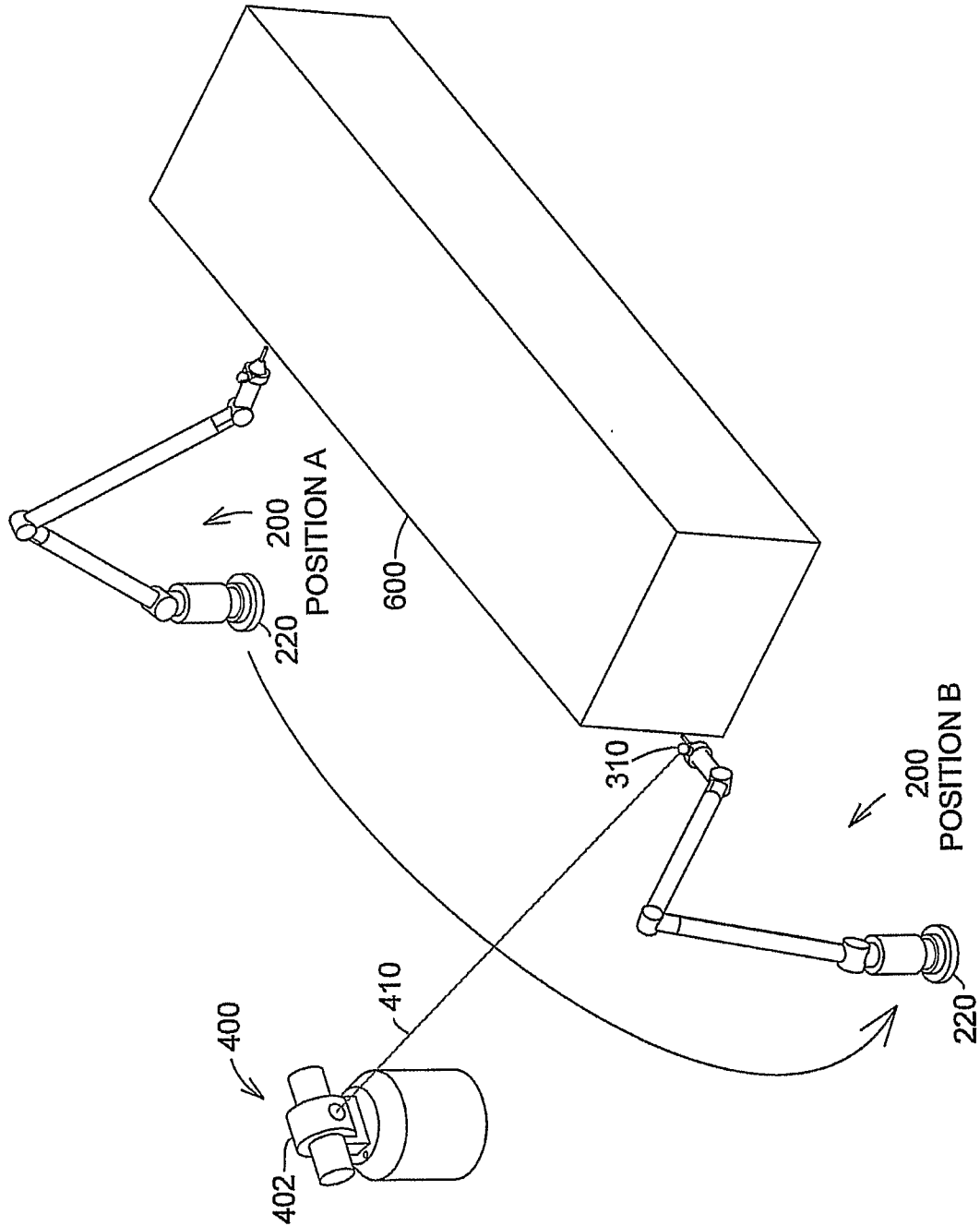


FIGURE 3

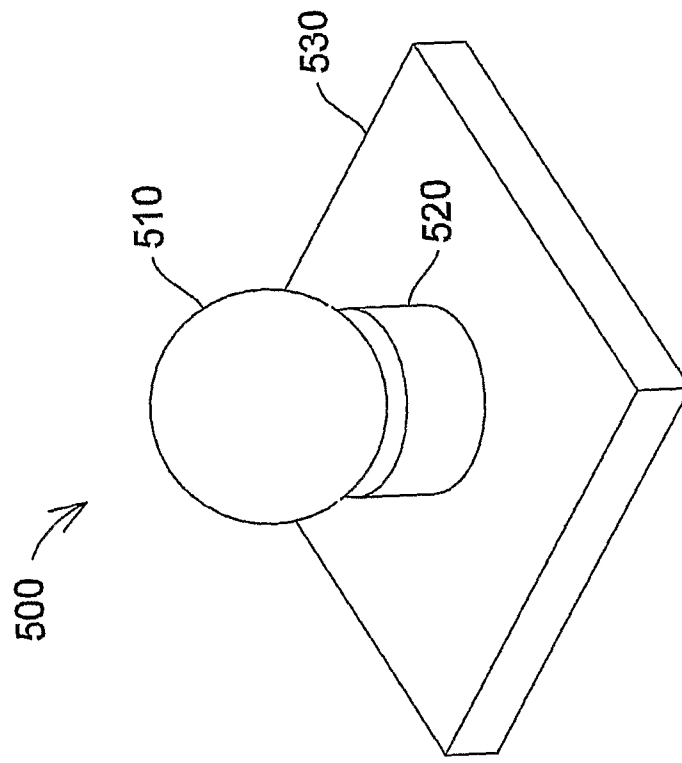


FIGURE 4

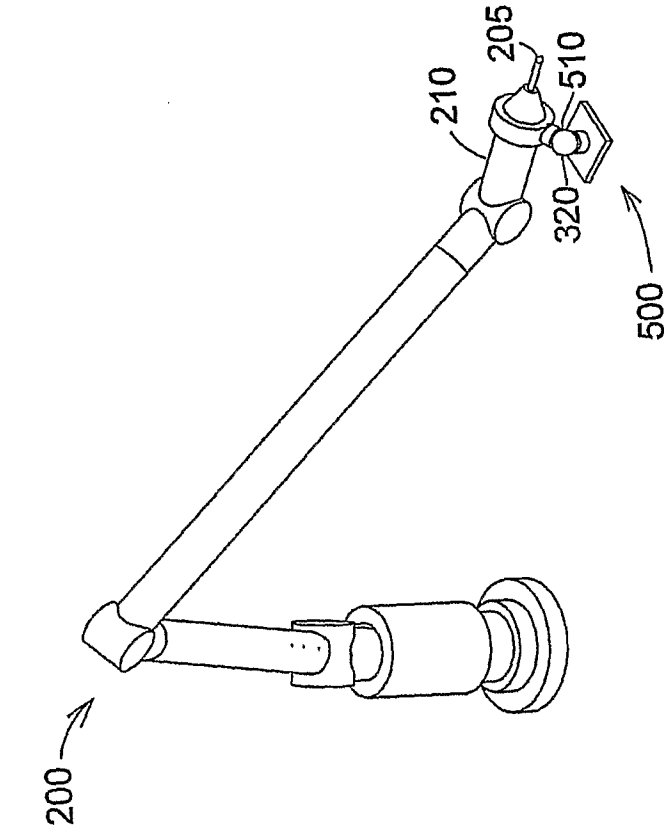


FIGURE 5A

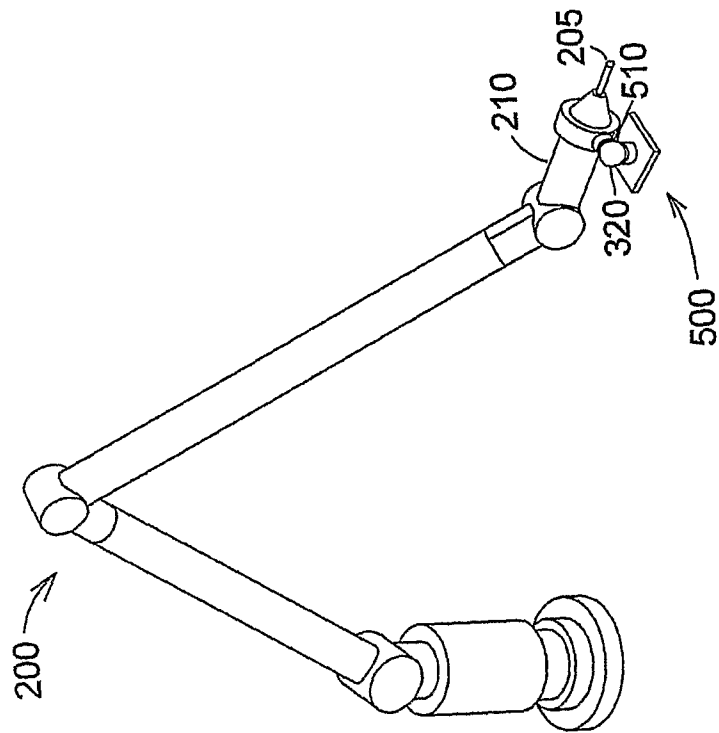


FIGURE 5B

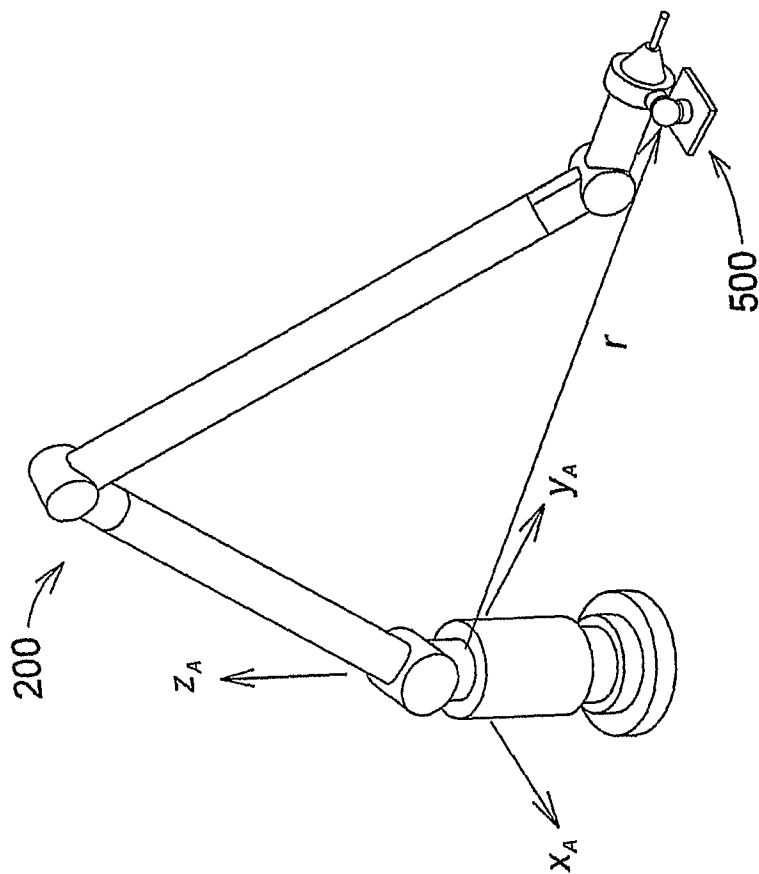


FIGURE 6A

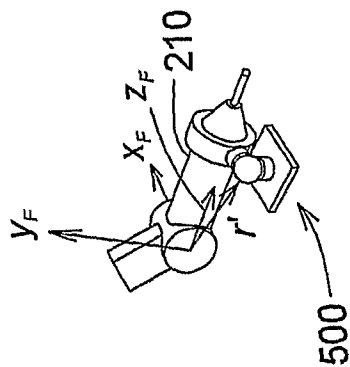


FIGURE 6B

**INTERNATIONAL SEARCH REPORT**

International application No  
PCT/US2006/024353

<b>A. CLASSIFICATION OF SUBJECT MATTER</b> INV. G01B21/04				
According to International Patent Classification (IPC) or to both national classification and IPC				
<b>B. FIELDS SEARCHED</b>				
Minimum documentation searched (classification system followed by classification symbols) B25J G01B				
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 practical, search terms used) EPO-Internal, WPI Data				
<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>				
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.		
X	US 2003/206285 A1 (LAU KAM C [US]) 6 November 2003 (2003-11-06) figures 1,6,7,10,11,14 paragraphs [0041] - [0043] paragraphs [0070] - [0075] paragraphs [0082] - [0084] paragraphs [0092], [0093]	1-11, 14		
X	US 2003/048459 A1 (GOOCH RICHARD MICHAEL [GB]) 13 March 2003 (2003-03-13) figure 1 paragraph [0015] - paragraph [0021] paragraph [0037] - paragraph [0039] paragraphs [0045], [0047], [0053]	1-11		
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<table style="width:100%; border: none;"> <tr> <td style="width:50%; border: none;"> <input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C.                 </td> <td style="width:50%; border: none;"> <input checked="" type="checkbox"/> See patent family annex.                 </td> </tr> </table>			<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C.	<input checked="" type="checkbox"/> See patent family annex.
<input checked="" type="checkbox"/> Further documents are listed in the continuation of Box C.	<input checked="" type="checkbox"/> See patent family annex.			
* Special categories of cited documents :				
<table style="width:100%; border: none;"> <tr> <td style="width:50%; border: none; vertical-align: top;">                 "A" document defining the general state of the art which is not considered to be of particular relevance                  "E" earlier document but published on or after the international filing date                  "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)                  "O" document referring to an oral disclosure, use, exhibition or other means                  "P" document published prior to the international filing date but later than the priority date claimed             </td> <td style="width:50%; border: none; vertical-align: top;">                 "T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention                  "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone                  "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.                  "&amp;" document member of the same patent family             </td> </tr> </table>			"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. "&" document member of the same patent family
"A" document defining the general state of the art which is not considered to be of particular relevance "E" earlier document but published on or after the international filing date "L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified) "O" document referring to an oral disclosure, use, exhibition or other means "P" document published prior to the international filing date but later than the priority date claimed	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention "X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone "Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art. "&" document member of the same patent family			
Date of the actual completion of the international search  <p align="center">20 October 2006</p>		Date of mailing of the international search report  <p align="center">27/10/2006</p>		
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016		Authorized officer  <p align="center">Bruinsma, Maarten</p>		

## INTERNATIONAL SEARCH REPORT

International application No  
PCT/US2006/024353

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6 069 700 A (RUDNICK FREDRICK C [US] ET AL) 30 May 2000 (2000-05-30) figures 1,2 column 4, line 50 - column 7, line 36 -----	9-11,14
X	US 4 691 446 A (PITCHES BRIAN E [GB] ET AL) 8 September 1987 (1987-09-08) figures 1,2 column 2, line 9 - column 3, line 19 -----	1-11
X	US 4 714 339 A (LAU KAM C [US] ET AL) 22 December 1987 (1987-12-22) the whole document -----	9-11,14

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Information on patent family members

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