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(54) Title: SYSTEM AND METHOD FOR PRECISE REAL-TIME CONTROL OF POSITION AND ORIENTATION OF TOOLING

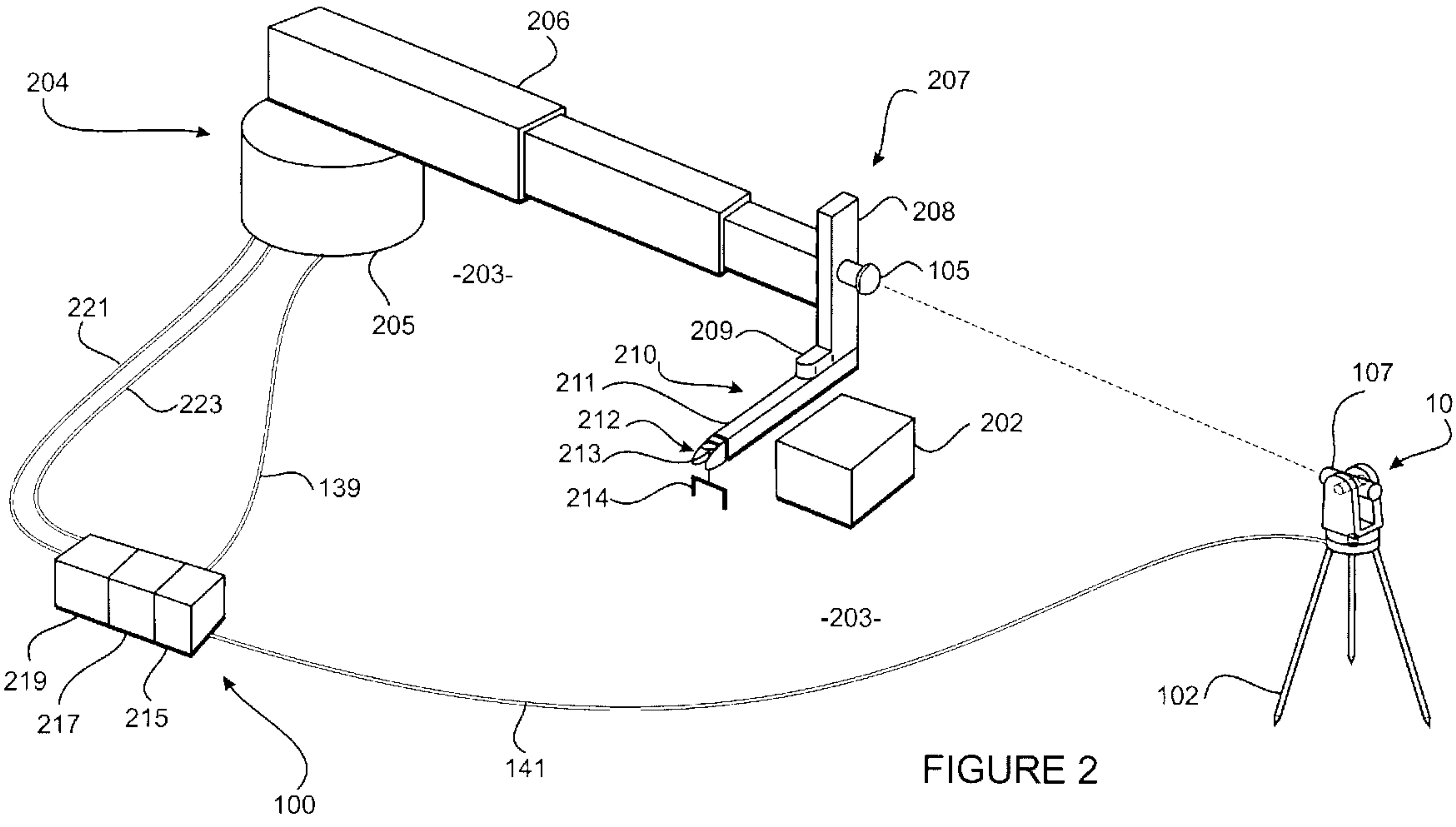

FIGURE 2

(57) Abrégé/Abstract:

A platform (204) supporting a raisable and pivotable robotic arm having a coarse positioning robotic arm (206) and at least one fine positioning robotic arm (210) is provided. The robotic arm is provided with apparatus for precise real-time measurement and control of the approximate position and orientation of the end (209) of the coarse positioning robotic arm relative to the position of a base (102). The base (102) has a distance sensor (107) with angle encoders arranged to send a beam to a target orientation sensor (105) located on said end (209) of the coarse positioning robotic arm (206), to measure and output spatial orientation data pertaining to the end (209). The target orientation sensor (103) outputs orientation data being a measurement of orientation of the end (209). Processor circuitry (100) derives data from the distance sensor (107) and the target orientation sensor (105), and uses this data in control of the approximate position of the end (209) by controlling the position of the coarse positioning robotic arm (206), and to control the position and orientation of the fine positioning robotic arm (210).

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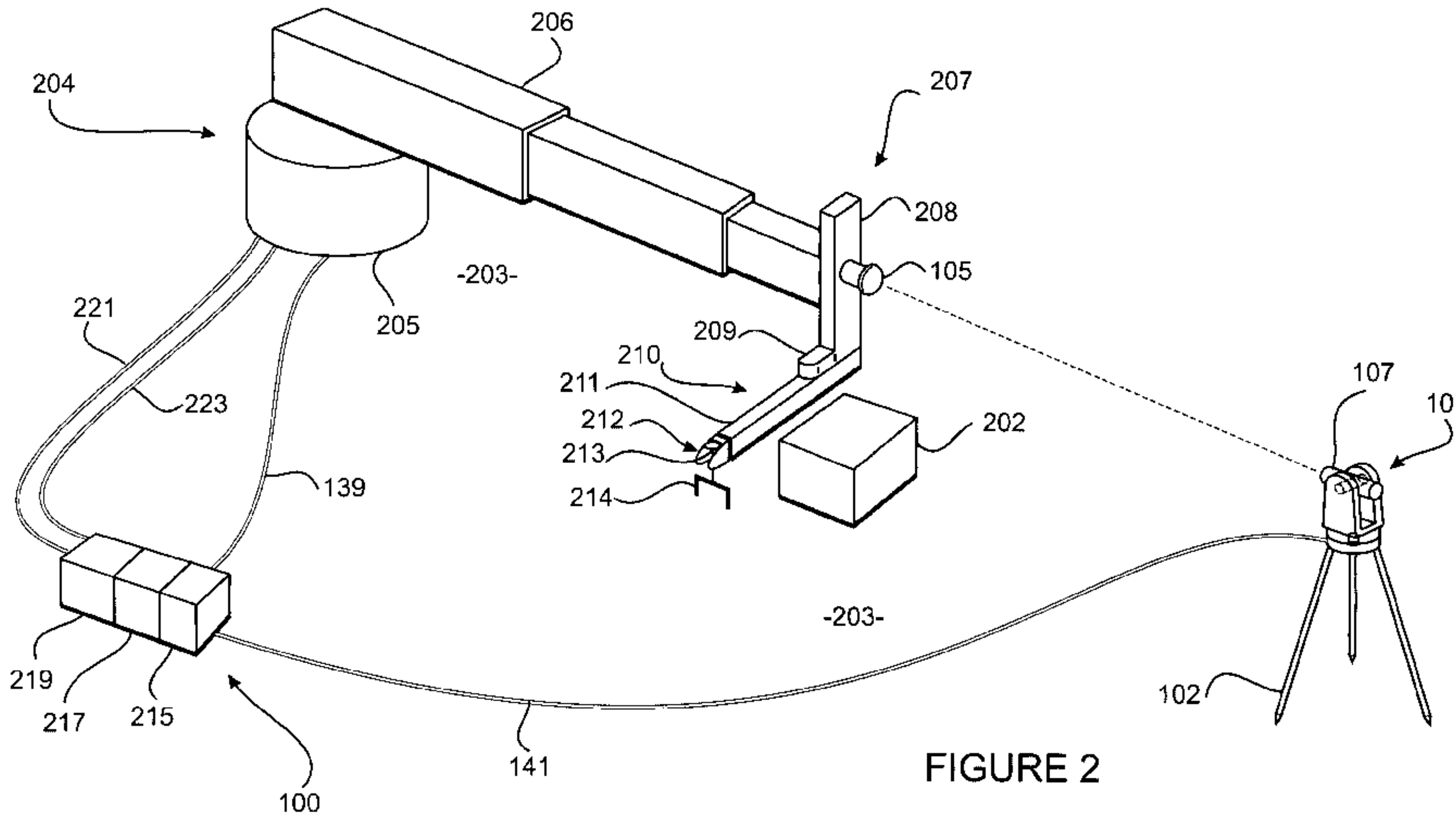

FIGURE 2

(57) Abstract: A platform (204) supporting a raisable and pivotable robotic arm having a coarse positioning robotic arm (206) and at least one fine positioning robotic arm (210) is provided. The robotic arm is provided with apparatus for precise real-time measurement and control of the approximate position and orientation of the end (209) of the coarse positioning robotic arm relative to the position of a base (102). The base (102) has a distance sensor (107) with angle encoders arranged to send a beam to a target orientation sensor (105) located on said end (209) of the coarse positioning robotic arm (206), to measure and output spatial orientation data pertaining to the end (209). The target orientation sensor (103) outputs orientation data being a measurement of orientation of the end (209). Processor circuitry (100) derives data from the distance sensor (107) and the target orientation sensor (105), and uses this data in control of the approximate position of the end (209) by controlling the position of the coarse positioning robotic arm (206), and to control the position and orientation of the fine positioning robotic arm (210).

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"System and Method for Precise Real-Time Control of Position and Orientation of Tooling"

Field of the Invention

This invention relates to the control of position and orientation in space of tooling. This invention has particular application in the control of position and orientation in space of tooling such as robotic manipulators and other robotic tools, the control of position and orientation in space of platforms, and the control of position in space of extendable and moveable arms and booms, both telescoping and articulated, while outputting position and orientation data which can be used in the control of position and orientation of attached tooling proximal to the target.

Background

In the field of machine tools, tools of various types fitted to machines to perform tasks. Typically if the task to be performed requires a high degree of precision then the machine performing the task must be rigid and restrained relative to the workpiece on which the task is performed. Control systems are employed on machines to move components of the machine, so that tools are moved relative to a workpiece to perform a required task. Examples of such arrangements include CNC (Computer Numeric Controlled) machining, laser cutting, water jet cutting, routing, robotic assembly, spray painting, glue deposition, automatic riveting and welding.

The requirement for the machine to be rigid, dynamically stable and well connected to the workpiece imposes size limitations on the work to be performed in that the machine needs to be relatively large when compared to the workpiece or working envelope of the machine. This can result in the machine being quite expensive as a result of the stiff and therefore massive structure which needs to be built to provide adequate rigidity, to achieve small deflection of the tooling relative to the workpiece. The large machine components require powerful and precise actuators to achieve accurate positioning and even with the best available actuators the machine operation is often limited by the dynamic structural response and deflection of the machine components caused by both external influences such as temperature and wind and the inertial forces induced by the machine motion and operation of the tooling.

The preceding discussion of the background to the invention is intended to facilitate an understanding of the present invention. However, it should be appreciated that the discussion is not an acknowledgement or admission that any of the material referred to was part of the common general knowledge in Australia or elsewhere as at the priority date of the application.

Throughout the specification, unless the context requires otherwise, the word "comprise" or variations such as "comprises" or "comprising", will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

Disclosure of the Invention

In accordance with the invention there is provided a robotic arm mounted to a platform, said robotic arm having a coarse positioning robotic arm with an end which is controllably moveable towards and away from said platform and controllably adjustable in altitude and azimuth relative to said platform;

said coarse positioning robotic arm being interfaced with an apparatus for precise real-time measurement and control of the approximate position and orientation of the end of the coarse positioning robotic arm relative to the position of a base,

said base having a distance sensor with angle encoders arranged to send a beam to a target orientation sensor located on said end of said coarse positioning robotic arm, to measure distance, bearing, and azimuth, and output spatial orientation data pertaining to said end of said robotic arm,

said target orientation sensor being mounted on a pan and tilt mechanism, said target orientation sensor being arranged through said pan and tilt mechanism to reflect said beam from said distance sensor back to said distance sensor, said target orientation sensor being arranged to output orientation data being a measurement of orientation of said end of said coarse positioning robotic arm,

said apparatus also including processor circuitry to derive first data being position and orientation data of said target, from said distance sensor and angle encoders and from said target orientation sensor, with respect to time,

said processor circuitry being used to control the position (and optionally where possible the orientation) of said end of said coarse positioning robotic arm in accordance with manually input or programmed data, and said position and orientation data set optionally being used as input in the control of the position (and optionally where possible the orientation) of said end of said coarse positioning robotic arm;

said robotic arm having at least one fine positioning robotic arm adjustably mounted to end of said coarse positioning robotic arm on an end mount, said fine positioning robotic arm having a tool mount located away from said end mount, for the mounting of a tool;

said processor circuitry also being used to control the position and orientation of said tool mount of said fine positioning robotic arm also in accordance with manually input or programmed data, and said position and orientation data set being used as input in the control of the position of said tool mount of said fine positioning robotic arm.

Preferably said fine positioning robotic arm has a range of movement able to compensate for resonant deflection in said coarse positioning robotic arm.

Preferably the fine positioning robotic arm has a natural (resonant) frequency of at least 6 times higher than that of the coarse positioning robotic arm.

Preferably the fine positioning robotic arm has a natural (resonant) frequency of from 7 to 60 times higher than that of the coarse positioning robotic arm.

Preferably the fine positioning robotic arm has a natural (resonant) frequency of from 10 to 30 times higher than that of the coarse positioning robotic arm.

Preferably the fine positioning robotic arm has a natural (resonant) frequency about 20 times higher than that of the coarse positioning robotic arm.

The coarse positioning robotic arm may be very large relative to the fine positioning robotic arm. The natural frequency of a structure is $f_n = k_1 \sqrt{(k_s/m)}$, where k_s is stiffness, k_1 is a factor dependent on geometry, m is mass, and f_n is natural frequency. In a servo mechanism it is not possible to cause an output to move controllably at a frequency higher than the natural frequency of the structure between the input actuator and the output. The coarse positioning robotic arm has low stiffness and large mass, and therefore, low natural frequency. The fine positioning robotic arm has high stiffness, low mass, and therefore high natural frequency. It will be appreciated that the natural frequency of the entire apparatus is dominated by the low natural frequency of the coarse positioning robotic arm.

Since the spatial positioning measurements are taken at the end of the coarse positioning robotic arm, it is possible to control at high bandwidth the fine positioning robotic arm so that any structural oscillation of the coarse positioning robotic arm can be compensated. Typically for a 25 metre long coarse positioning robotic arm, the dominant structural modes are at 0.5 to 2 Hz. For a 1 metre working envelope fine positioning robotic arm, the dominant structural modes are at 15 to 30 Hz. Therefore it can be seen that in an implementation of the fine positioning system bandwidth is an order of magnitude higher than the coarse positioning bandwidth.

With this arrangement, deflection in the end of the coarse positioning robotic arm brought about for example by wind blowing against the coarse positioning robotic arm can be compensated by controlling the position and orientation of the tool mount of the fine positioning robotic arm.

The distance, altitude and azimuth data may be a direct measure of distance, altitude and azimuth from the base to the end of the coarse positioning robotic arm, or may be derived data providing the position of the end of said coarse positioning robotic arm in three co-ordinates (x,y,z) from the base. The orientation data provides at least pitch and yaw data pertaining to the end of said coarse positioning robotic arm, relative to the base. It will be understood that since the position of the base relative to the platform is known, the position of the end of the coarse positioning robotic arm, relative to the platform and the position of the tool mount relative to the platform is being controlled. As the position and orientation of the end of the coarse positioning robotic arm can differ from the position and orientation of the tool mount, the processor circuitry operates to transform the position and orientation of the end of the coarse positioning robotic arm to a desired position and orientation of the tool mount, by mapping the co-ordinates of the end of the coarse positioning robotic arm to the desired co-ordinates of the tool mount, when controlling the fine positioning robotic arm.

Preferably said distance sensor measures distance with a laser interferometer.

Alternatively said distance sensor measures distance by time of flight measurement.

Preferably said apparatus also has an inertial reference system including motion sensors in or on said target to measure linear and angular acceleration in said target, said processor circuitry being operable to process measurements from said motion sensors to derive second data also being position and orientation data of said target also with respect to time, said processor circuitry being operable to combine said first data and said second data to generate a single data set of position and orientation of said target with respect to time, said output outputting said single data set of position and orientation of said target.

Preferably said first data and said second data are combined by said processor circuitry using a Kalman filter to generate said single data set of position and orientation of said target with respect to time.

Preferably said target orientation sensor includes a roll sensor, to detect roll of said target in addition to yaw and pitch (pan and tilt).

Preferably said processor circuitry is used to control both the position and orientation of said end of said coarse positioning robotic arm in accordance with manually input or programmed data, and said position and orientation data set being used as input in the control of the position and orientation of said end of said coarse positioning robotic arm.

Preferably the output data rate of time-averaged data output of the distance sensor with angle encoders lies in the range of from about 1 Hz to about 10 kHz.

Preferably the output data rate of time-averaged data output of the distance sensor with angle encoders lies in the range of from about 5 Hz to about 1 kHz.

Preferably the output data rate of time-averaged data output of the distance sensor with angle encoders lies in the range of from about 10 Hz to about 100 Hz.

Preferably the output data rate of time-averaged data output of the target orientation sensor encoders lies in the range of from about 1 Hz to about 10 kHz.

Preferably the output data rate of time-averaged data output of the target orientation sensor encoders is the same as the output data rate of time-averaged data output of the distance sensor with angle encoders.

Preferably the output data rate of the inertial reference system lies in the range of from 10 Hz to 100 kHz.

Preferably the output data rate of the inertial reference system lies in the range of from 50 Hz to 10 kHz.

Preferably the output data rate of the inertial reference system lies in the range of from 100 Hz to 1 kHz.

Preferably the ratio of output data rate of time-averaged data output of the distance sensor with angle encoders and the target orientation sensor, and the output data rate of the inertial reference system is from about 1:5 to about 1:100.

Preferably the ratio of output data rate of time-averaged data output of the distance sensor with angle encoders and the target orientation sensor, and the output data rate of the inertial reference system is from about 1:10 to about 1:50.

Preferably the ratio of output data rate of time-averaged data output of the distance sensor with angle encoders and the target orientation sensor encoders and the output data rate of the inertial reference system is about 1:25.

It will be appreciated that the distance sensor with angle encoders, and the target orientation sensor, sample data internally at a data rate which is not necessarily related to the output data rate. Typically the rate at which successive measurements are taken or the internal sampling data rate of these instruments, will be very much higher that the output data rate. Successive measurements may be averaged over time for a whole or part of the period between successive output data.

The tool mount may be arranged to have fitted a robotic manipulator, a camera, or a horizontally disposed platform, depending upon the application to which the invention is intended to be put.

It should be noted that the flexibility is relative to the size of the workspace. Thus this invention has applications for both large and small items.

This invention has specific applications in the fields of constructing and fitting out buildings, automated bricklaying, painting large structures, automatic welding, machining of large structures, ship building, ship painting, large scale dot matrix or bubble jet printing, profile cutting, robotic assembly, pavement application, concrete finishing, mining, drill and blast, forestry harvesting, gunnery, artillery, surgery, anti terrorist activities such as bomb disposal. If the end tool includes an extrusion, fusion, curing or dispensing device a very large scale construction machine can be built that constructs an entire building layer by layer as a homogenous unit, in similar fashion to that employed by small scale FDM, SLS or stereolithography.

Also in accordance with the invention there is provided a method of controlling a robotic arm mounted to a platform, said robotic arm having a coarse positioning robotic arm with an end which is controllably moveable towards and away from said platform and controllably adjustable in altitude and azimuth relative to said platform, said method comprising:

interfacing said coarse positioning robotic arm with an apparatus for precise real-time measurement and control of the approximate position and orientation of the end of the coarse positioning robotic arm relative to the position of a base located spatially therefrom,

locating a target orientation sensor at or near an end of said coarse positioning robotic arm,

providing said base with a distance sensor with angle encoders arranged to send a beam to a target orientation sensor located on said end of said coarse positioning robotic arm, and to measure distance, bearing, and azimuth, and output spatial orientation data pertaining to said end of said robotic arm,

said target orientation sensor being mounted on a pan and tilt mechanism, said target orientation sensor being arranged through said pan and tilt mechanism to reflect said beam from said distance sensor back to said distance sensor, said target orientation sensor being arranged to output orientation data being a measurement of orientation of said end of said coarse positioning robotic arm,

providing processor circuitry to derive first data being position and orientation data of said target, from said distance sensor and angle encoders and from said target orientation sensor, with respect to time, using said processor circuitry to control the position (and optionally where possible the orientation) of said end of said coarse positioning robotic arm in accordance with manually input or programmed data, and said position and orientation data set optionally being used as input in the control of the position (and optionally where possible the orientation) of said end of said coarse positioning robotic arm;

providing said said robotic arm with at least one fine positioning robotic arm adjustably mounted to the end of said coarse positioning robotic arm on an end mount, said fine positioning robotic arm having a tool mount located away from said end mount, for the mounting of a tool;

using said processor circuitry to control the position and orientation of said tool mount of said fine positioning robotic arm also in accordance with manually input or programmed data, and using said position and orientation data set as input in the control of the position of said tool mount of said fine positioning robotic arm.

Brief Description of the Drawings

The present invention shall be explained by way of the following description of a preferred embodiment made with reference to the drawing in which:

Figure 1 is an orthographic diagram showing the apparatus of the embodiment in an application for controlling the position and orientation of the end of a boom;

Figure 2 is an orthographic view showing the apparatus of the embodiment in use on a boom for a robotic arm; and

Figure 3 is a part orthographic view of part of the robotic arm shown in figure 2, illustrating an alternative embodiment.

Best Mode(s) for Carrying Out the Invention

The embodiment present invention provides a coarse positioning system and mechanism and a fine positioning system and mechanism coupled to a measurement and control system that measures via a non contact method, the position and orientation of machine components close to the tooling, from a coordinate system fixed relative to a workpiece. The coarse positioning system provides an approximate position. The deflected dynamic position and orientation of the end of the coarse positioning mechanism is measured in real time and this measured position and orientation of the base of the fine positioning system is used to calculate an offset that is added as a position transformation to the relative position of the fine positioning mechanism so that the tooling is positioned in the correct place at the correct orientation relative to the workpiece. Thus a large and relatively light and flexible structure can be used to approximately position a fast and accurate fine positioning mechanism that can in real time accurately control and move a tool relative to a workpiece in an accurate and fast motion.

The present invention also removes the requirement for the workpiece and tooling to be rigidly connected. If the workpiece has adequate stability due to its mass and support then the coarse positioning system may include a mobile unit that can move it over a large area. Such a mobile unit may consist of a tracked or wheeled vehicle, a moveable frame, a floating vessel or a flying craft such as a helicopter.

The sensing of position and orientation is provided by a non contact position and orientation measurement system which may be provided by a laser tracker and orientation tracker such as an API Laser Tracker 3 and Target Orientation Sensor such as a SmartTrack Sensor. A laser tracker is an accurate measurement instrument that uses a laser distance measuring sensor and two accurate angle encoders to measure distance, bearing and azimuth to a target. A Target Orientation Sensor is any sensor that can provide an accurate measurement of the orientation of a target. This consists of a sensor that is mounted on a pan and tilt mechanism that looks back at the laser tracker and can also make a roll measurement. It is extremely advantageous from a dynamic control standpoint to have accurate acceleration data available to the control system, so it is advantageous to include a six degree of freedom inertial navigation system or three orthogonal accelerometers and three orthogonal angular rate gyros.

The distance sensor used on a laser tracker may be a time of flight sensor or a laser interferometer. A time of flight distance sensor transmits a pulse of laser light that is reflected off a target and returns to the sensor. The time of flight is measured and knowing the speed of light allows the distance to be calculated. A laser interferometer sends a beam of light through a beam splitter prism that sends a first beam to a target mirror that retro reflects the light of the first beam back to the interferometer. The first beam is then combined against the second beam from the beam splitter prism and the resultant beam experiences an interference due to the phase difference of the coherent light in the two beams. As the target mirror is moved towards or away from the interferometer the phase relationship of the two beams changes. The interferometer has a sensor that measures the interference of the two beams and counts the “interference fringes”. The measurement must start with the target mirror located at a precise known position relative to the interferometer and then distance changes are measured by counting the “interference fringes”. In the preferred embodiment the laser light first passes thorough a polarising filter so that the light beam is polarised and can be detected by the roll sensor of the target orientation sensor.

The target orientation sensor “looks back” at the laser tracker light beam. Light enters the sensor telescope and passes through a beam splitting prism. The first beam passes through a second beam splitter prism to create a third beam. The first beam then travels to a retro reflective mirror that provides the target for the distance sensor and reflects the first beam back to the distance sensor. The second beam passes to a CCD (charge coupled device) sensor array that is used as a control signal to the controller that moves the pan and tilt motors to make the target orientation sensor track the Laser Tracker. The third beam passes to a polarised light sensor. The polarised light sensor determines the polarisation angle of the laser light and therefore provides a roll measurement for the target orientation sensor.

In the following descriptions of the embodiment, some off-the-shelf componentry is used. Specific model numbers of manufacturers off-the-shelf equipment is used in the description to provide an example of physical implementation. From this information, persons skilled in the art will appreciate that alternative equipment could be used and would be within the scope of the present invention.

Referring to figure 1, the basic sensors and control systems that are normally employed separately in an inertial reference system and a combined laser tracker and orientation sensor, are combined and controlled by a single computer 100. Raw data values are buffered so that the data is immediately available to the computer when required. Digital filtering used individually on each channel to filter and condition the digital data. The input of data to the computer and the initial filtering of individual inputs utilises standard known techniques.

Referring to figures 1 and 2, a laser tracker 101 provided by an Automated Precision Inc. "OmniTrac^{TM}" time of flight distance sensor with angle encoders is mounted to a base in the form of a tripod 102. Referring to figure 1, an orientation sensor 105 provided by an Automated Precision Inc. “SmartTRACK^{TM}” orientation sensor, and an inertial reference system 104 being an IMAR iNAV-RQH-1004 are mounted to a target or head 105.

The laser tracker 101 includes a pan and tilt angle measurement mechanism 106 and a range finder 107. The laser tracker 101 has a first pan axis 109 and a second tilt axis 111. The laser tracker 101 has a time of flight range-finder 107, and sends a beam of polarised light to a target mirror (contained in the orientation sensor 103) that retro reflects the light of the first beam back to the rangefinder.

The orientation sensor 103 includes a pan 113, tilt 115 and roll tracking mechanism 117 that looks back at the laser tracker 101. The orientation sensor 103 has a first pan axis 119, a second tilt axis 121 and a third roll axis 123. The head 105 also includes three orthogonal angular gyroscopes 125, 127 and 129 and three orthogonal linear accelerometers 131, 133 and 135. The roll tracking mechanism 117 detects the polarised light emitted by the polarised light source of the laser tracker 101 and provides a roll angle relative to the base laser tracker 101 (or horizontal plane through the second tilt surface – assuming the tripod 102 is mounted horizontally on horizontal ground). In the preferred embodiment the angular gyroscopes 125, 127 and 129 are ring laser gyroscopes but in other embodiments could be any other type of suitable angular or rate gyroscope such as a strapped down MEMS gyroscope, galvanometer or mechanical (spinning disk) gyroscope, or fibre optic gyroscope.

The laser tracker is an accurate measurement instrument that uses a laser distance measuring sensor and two accurate angle encoders to measure distance, altitude and azimuth to a target. The laser tracker sends a beam of polarised light from the base to the target. The orientation sensor provides an accurate measurement of the orientation of a target, and effectively comprises a sensor that is mounted on a pan and tilt mechanism that “looks back” at the laser tracker, reflecting the beam of light back to the laser tracker and measurements are made of pan and tilt angles at the orientation sensor. The orientation sensor can also make a roll measurement through use of a roll sensor using a polarising filter which is rotated, and measurement of the rotation is taken to determine the angle of polarisation of the light from the laser tracker, and hence the rotational angle of the target relative to the base.

In an alternative embodiment, the distance sensor used on a laser tracker may be a laser interferometer such as an Automated Precision Inc. “Tracker3^{TM}” laser tracker. A time of flight distance sensor as used in the embodiments described here, transmits a pulse of laser light that is reflected off a target and returns to the sensor. The time of flight is measured and knowing the speed of light allows the distance to be calculated. A laser interferometer laser tracker sends a beam of light through a beam splitter prism that sends a first beam to a target mirror that retro reflects the light of the first beam back to the interferometer. The first beam is then combined against the second beam from the beam splitter prism and the resultant beam experiences an interference pattern due to the phase difference of the coherent light in the two beams. As the target mirror is moved towards or away from the interferometer the phase relationship of the two beams changes. The interferometer has a sensor that measures the interference pattern of the two beams and counts the “interference fringes”. With a laser interferometer laser tracker, the measurement must start with the target mirror located at a precise known distance relative to the interferometer and then distance changes are measured by counting the “interference fringes”. In such an alternative embodiment the laser light first passes thorough a polarising filter so that the light beam is polarised and the angle of polarisation can be detected by the roll sensor of the orientation sensor in the target.

As stated above, the orientation sensor looks back at the laser tracker light beam. Light enters the orientation sensor telescope and passes through a beam splitting prism. The first beam passes through a second beam splitter prism to create a third beam. The first beam then travels to a retro reflective mirror that provides the target for the distance sensor and reflects the first beam back to the distance sensor. The second beam passes to a CCD (charge coupled device) sensor array that is used as a control signal to the controller that moves the pan and tilt motors to make the orientation sensor track the laser tracker. The third beam passes to the roll sensor. The roll sensor determines the polarisation angle of the laser light and therefore provides a roll measurement for the orientation sensor.

Both the combined laser tracker and the orientation sensor process their data via computer 100. The position and orientation data is time averaged, and output at a data rate of 10 Hz. The inertial reference system position and orientation data is output at a data rate of 250 Hz. The combined laser tracker and the orientation sensor and inertial reference system data are combined by computer 100. Effectively, the data from the combined laser tracker and the orientation sensor is used to correct for gyroscopic drift inherent in the inertial reference system.

All rotary axes on the pan and tilt mechanisms 106 and 113, 115 have high accuracy encoders (not shown) that provide accurate digital angle measurement and servo motors (also not shown) that provide accurate motion. The servo motors are connected to amplifiers 137 via cables 139 and 141 so that the tracking system operates in a closed loop according to well known industrial motion control methods. In a most preferred arrangement, the servo motors are direct drive torque motors.

The encoders provide angle measurement to the computer 100. The computer 100 combines the angle measurements received from the axes 109, 111, 119, 121 and 123 and the distance measurement from the range finder 107 to determine the relative position and orientation of the head 105 from the base 102. The position of the base 102 relative to a world datum can be determined by moving the head to that datum and back calculating. At least three world datums are required to provide all six positional coordinates. This is done by known surveying principles and trigonometry. By combining the known base 102 position with the relative head 105 position, the absolute direct position of the head 105 can be calculated.

The computer 100 also receives acceleration data from the linear accelerometers 131, 133 and 135 and orientation or orientation acceleration (depending on the type of sensor 125-129) information from the angular gyros 125, 127 and 129. By using a dead reckoning algorithm the computer 100 integrates the acceleration data over time including orientation effects to obtain velocity information and integrates the velocity information over time including orientation effects to obtain inertial relative positional information.

The computer 100 then repetitively combines the inertial relative positional information with the absolute direct position through a Kalman or other suitable filtering algorithm to generate a single set of time stamped position, velocity and acceleration data for all six degrees of freedom. The Kalman filter must be tuned to provide optimum output. To understand the filtering process in lay terms, an approximation is that the combined laser tracker and the orientation sensor data is low pass filtered while the inertial reference system data is high pass filtered.

By way of explanation, the optimum Kalman filter combines a predicted data set with a measured data set to give a filtered data set. The predicted data set is obtained by using the previously obtained filtered data set and a model of the system combined with control data and structural dynamics information to predict the current data set. The measured data set is obtained from the instrumentation. The combination algorithm first compares the measured data with the predicted data to check that the measured data is within range and does not contain excessive noise or null values. If the measurements are out of range they are trimmed back to the limit value. If the measurements are null values they are set to the predicted value. The next step of the algorithm calculates a weighted average of the predicted data and the measured data. For the optimum Kalman Filter the covariance matrix of the measurement variables can be used to determine the optimum Kalman Filter gain. Alternatively optimised values can be determined by experiment.

In the six degree of freedom case the system is governed by Newtons laws of motion. In the general case the mass and intertia may change with time due to changes in machine (target) pose, configuration or payload. Measurements from the inertial reference system are in units of acceleration and therefore the predicted motion is independent of mass and inertia changes. The control inputs are generally in terms of force input (via actuators) and therefore the resultant motion does depend on the machine mass and inertia. Structural dynamics are pose, configuration, mass and inertia dependant. The structural dynamics can be considered as the sum of static deflection and oscillatory response. Whilst it is possible to model all of these effects it is computationally efficient to make simplifications that have little effect on the accuracy.

In an ideal application of this technology, the mass is large compared to the exciting force so that the acceleration due to control or disturbance will be low.

A linear forward prediction over a short timeframe, of eg 4ms, experiences effectively no influence from any external or internally applied force because acceleration has so little effect on displacement ($s=ut+0.5at^2$).

Peak accel = $4ms^{-2}$,
t=0.004s,
displacement = s = 0.032mm.

The relative displacement from control cycle to cycle really depends only on the current velocity. The displacement due to acceleration is a second order effect and can be discounted. This means that short term latency or delays in the control cycles are not a problem provided they are consistent. At 10ms the potential error may start to become significant. Velocity and latency has a much greater effect, for example at 600mm/sec, a 1ms variation in latency would change the predicted position by 0.6mm (ie 20x the effect of the worst case external transient force).

This is advantageous because it means that all of the uncertainty due to acceleration variation is of second order effect and of little consequence over one time cycle. The system state model is thereby reduced to one of position and velocity while the measurements are of position by the combined laser tracker and orientation sensor and acceleration measured by the inertial reference system. The inertial reference system acceleration measurements are used for the prediction.

Regarding the level of accuracy achieved, the combined laser tracker and orientation sensor achieves 10um ± 1ppm and outputs every 10ms. The inertial reference system can output every 1ms and a drift rate of 1000mm/hr which over 10ms has drift of the order of 2.7µm. Therefore the combined system can output measurements at 1ms interval with an error not exceeding 13µm ± 1ppm.

Referring to Figure 2 a non contact first measurement instrument in the form of the laser tracker 101 set on the tripod 102 is set up so that it is fixed relative to a workpiece 202. In this preferred embodiment the workpiece 202 is rested on the ground 203 and the laser tracker 101 set on the tripod 102 rested on the ground.

A robotic arm 204 is set on a platform 205 which may or may not be directly attached to the workpiece 202. In the preferred embodiment the platform 205 rests on the ground 203.

The base 205 supports a coarse positioning robotic arm comprising a telescopic boom 206 with a vertically travelling column 208 at the end 207 of the boom 206.

The telescopic boom 206 is mounted to the platform 205 about a joint which may pivot about both a horizontal axis allowing the boom to be raised and lowered (altitude), and a vertical axis allowing the boom to be rotated horizontally (azimuth).

Those skilled in the art will appreciate that the coarse positioning robotic arm could consist of any type of mechanism that can move a second end relative to a first end. Such mechanisms include but are not limited to industrial robots, cranes, booms, telescopic booms, SCARA arms, overhead gantry or manipulators with any combination of articulated and sliding joints, gantries or machine tools.

The target or head 105 is attached at the end of the telescopic boom 206 to the vertically travelling column 208, and so measures the combined position and orientation of the coarse positioning robotic arm 206 and vertically travelling column 208.

The vertically travelling column 208 has mounted there to, base 209 to which is attached a fine positioning robotic arm 210. The fine positioning robotic arm 210 has a horizontal bar 211 which moves slidingly in a horizontal manner relative to the base 209 and vertically travelling column 208, and also moves rotatably about the base 209. The fine positioning robotic arm 210 includes at an end located away from the base 209 connection with the vertically travelling column 208, a robot manipulator 212 having a tool mount 213 in which is mounted a robotic gripper 214.

The fine positioning robotic arm 210 may be any type of robot or manipulator that allows movement in at least five and preferably six degrees of freedom. In the embodiment shown the fine positioning robotic arm 210 is an r, theta, z robot manipulator with a three axis wrist.

In an alternative embodiment, the fine positioning robotic arm may incorporate the vertically travelling column 208, and the target or head 105 can be attached directly to the end of the telescoping boom 206.

The laser tracker 101 and the target or head 105 communicatively connected 141, 139 to the computer 100 which includes a measurement processing unit 215. The communication connection may be by physical connection such as a serial data cable as shown in figure 2, or ethernet cable or fibre optic or by a data transmission wireless link, in alternative arrangements .

The measurement system processing unit 215 calculates the position and orientation in real time of the vertically travelling column 208 to which the fine positioning robotic arm 210, 212 is attached.

The coarse positioning robotic arm formed by the telescopic boom 206 and the vertically travelling column 208 is controlled by a control computer system 217. The measurement system processing unit 215 communicates the position and orientation of the vertically travelling column 208 to the control computer system 217. The control computer system 217 compares the actual position and orientation of the vertically travelling column 208 to the desired position and orientation and thereby calculates a six degree of freedom error vector. The control computer system 217 then calculates the required axis positions and motion parameters of the fine positioning robotic arm comprising the fine positioning robotic arm 210 and the robot manipulator 212, taking into account the six degree of freedom error vector so that the tool mount 213 and robotic gripper 214 are positioned at the required orientation relative to the workpiece 202. Acceleration measurements available from linear accelerometers and rate gyros, are used to calculate acceleration feedforward which is combined using the Kalman filter previously discussed, to improve motion dynamics.

The axis positions and motion parameters are then used by motion control 219 to move the axes to the required positions. The motion control 219 is connected via cables 221 and hoses 223 to the telescopic boom 206 and the vertically travelling column 208 and fine positioning robotic arm 210, the robot manipulator 212 and the gripper 214.

Referring to figure 3, an alternative vertically travelling column 208 and fine positioning robotic arm 210 is shown. The base 209 is mounted on a track 231 located in the vertically travelling column 208 for fine vertical positioning of the fine positioning robotic arm 210. The base 209 is connected to the horizontal bar 211 of the fine positioning robotic arm 210 by a column 233 which stands off the horizontal bar 211 from the vertically travelling column in order to provide clearance when the base 209 is raised up the track 231. A carriage 235 is rotatably fitted to the bottom of the column 233, the carriage providing sliding support for the horizontal bar 211.

Those skilled in the appropriate arts will appreciate that multiple fine positioning robotic arms could be incorporated so that multiple tasks may be undertaken. Various delivery mechanisms such as pipes and hoses or conveyor belts may be added to the boom 206 to deliver materials and or components or tooling to the end 207 of the boom 206 or the column 208 so that they may be used by the gripper 214.

It should be appreciated that the scope of the invention is not limited to the particular embodiment disclosed herein.

The Claims Defining the Invention are as Follows

1. A robotic arm mounted to a platform, said robotic arm having a coarse positioning robotic arm with an end which is controllably moveable towards and away from said platform and controllably adjustable in altitude and azimuth relative to said platform;

said coarse positioning robotic arm being interfaced with an apparatus for precise real-time measurement and control of the approximate position and orientation of the end of the coarse positioning robotic arm relative to the position of a base,

said base having a distance sensor with angle encoders arranged to send a beam to a target orientation sensor located on said end of said coarse positioning robotic arm, to measure distance, bearing, and azimuth, and output spatial orientation data pertaining to said end of said robotic arm,

said target orientation sensor being mounted on a pan and tilt mechanism, said target orientation sensor being arranged through said pan and tilt mechanism to reflect said beam from said distance sensor back to said distance sensor, said target orientation sensor being arranged to output orientation data being a measurement of orientation of said end of said coarse positioning robotic arm,

said apparatus also including processor circuitry to derive first data being position and orientation data of said target, from said distance sensor and angle encoders and from said target orientation sensor, with respect to time,

said processor circuitry being used to control the position (and optionally where possible the orientation) of said end of said coarse positioning robotic arm in accordance with manually input or programmed data, and said position and orientation data set optionally being used as input in the control of the position (and optionally where possible the orientation) of said end of said coarse positioning robotic arm;

said robotic arm having at least one fine positioning robotic arm adjustably mounted to end of said coarse positioning robotic arm on an end mount, said fine positioning robotic arm having a tool mount located away from said end mount, for the mounting of a tool;

said processor circuitry also being used to control the position and orientation of said tool mount of said fine positioning robotic arm also in accordance with manually input or programmed data, and said position and orientation data set being used as input in the control of the position of said tool mount of said fine positioning robotic arm.

2. A robotic arm as claimed in claim 1 wherein said distance sensor measures distance with a laser interferometer.

3. A robotic arm as claimed in claim 1 wherein said apparatus also has an inertial reference system including motion sensors in or on said target to measure linear and angular acceleration in said target, said processor circuitry being operable to process measurements from said motion sensors to derive second data also being position and orientation data of said target also with respect to time, said processor circuitry being operable to combine said first data and said second data to generate a single data set of position and orientation of said target with respect to time, said output outputting said single data set of position and orientation of said target.

4. A robotic arm as claimed in claim 3 wherein said first data and said second data are combined by said processor circuitry using a Kalman filter to generate said single data set of position and orientation of said target with respect to time.

5. A robotic arm as claimed in any one of the preceding claims wherein said target orientation sensor includes a roll sensor, to detect roll of said target in addition to yaw and pitch (pan and tilt).

6. A robotic arm as claimed in any one of the preceding claims wherein said processor circuitry is used to control both the position and orientation of said end of said coarse positioning robotic arm in accordance with

manually input or programmed data, and said position and orientation data set being used as input in the control of the position and orientation of said end of said coarse positioning robotic arm.

7. A method of controlling a robotic arm mounted to a platform, said robotic arm having a coarse positioning robotic arm with an end which is controllably moveable towards and away from said platform and controllably adjustable in altitude and azimuth relative to said platform, said method comprising:

interfacing said coarse positioning robotic arm with an apparatus for precise real-time measurement and control of the approximate position and orientation of the end of the coarse positioning robotic arm relative to the position of a base located spatially therefrom,

locating a target orientation sensor at or near an end of said coarse positioning robotic arm,

providing said base with a distance sensor with angle encoders arranged to send a beam to a target orientation sensor located on said end of said coarse positioning robotic arm, and to measure distance, bearing, and azimuth, and output spatial orientation data pertaining to said end of said robotic arm,

said target orientation sensor being mounted on a pan and tilt mechanism, said target orientation sensor being arranged through said pan and tilt mechanism to reflect said beam from said distance sensor back to said distance sensor, said target orientation sensor being arranged to output orientation data being a measurement of orientation of said end of said coarse positioning robotic arm,

providing processor circuitry to derive first data being position and orientation data of said target, from said distance sensor and angle encoders and from said target orientation sensor, with respect to time,

using said processor circuitry to control the position (and optionally where possible the orientation) of said end of said coarse positioning robotic arm in accordance with manually input or programmed data, and said position and orientation data set optionally being used as input in the control of the position (and optionally where possible the orientation) of said end of said coarse positioning robotic arm;

providing said said robotic arm with at least one fine positioning robotic arm adjustably mounted to the end of said coarse positioning robotic arm on an end mount, said fine positioning robotic arm having a tool mount located away from said end mount, for the mounting of a tool;

using said processor circuitry to control the position and orientation of said tool mount of said fine positioning robotic arm also in accordance with manually input or programmed data, and using said position and orientation data set as input in the control of the position of said tool mount of said fine positioning robotic arm.

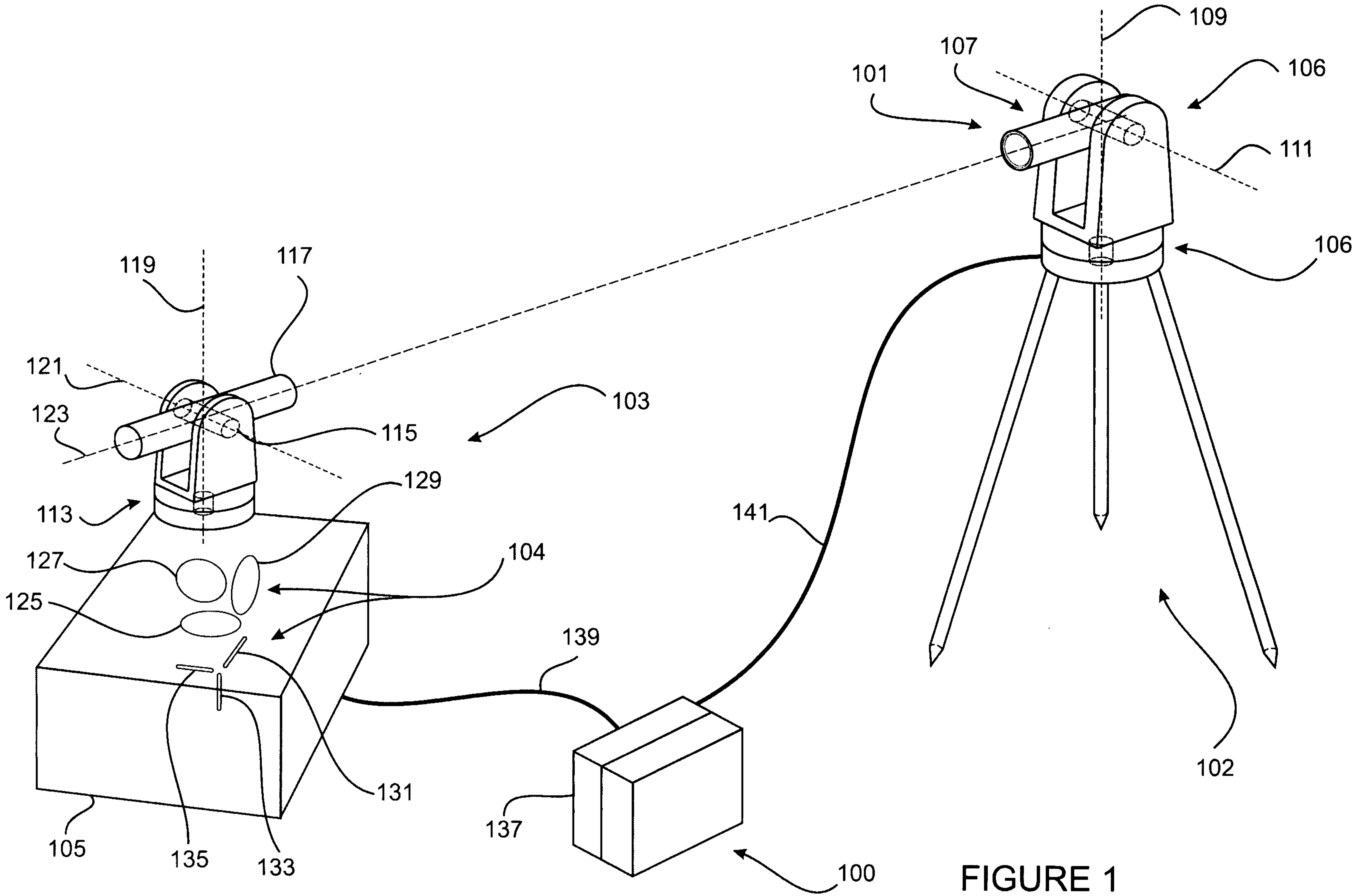
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FIGURE 1

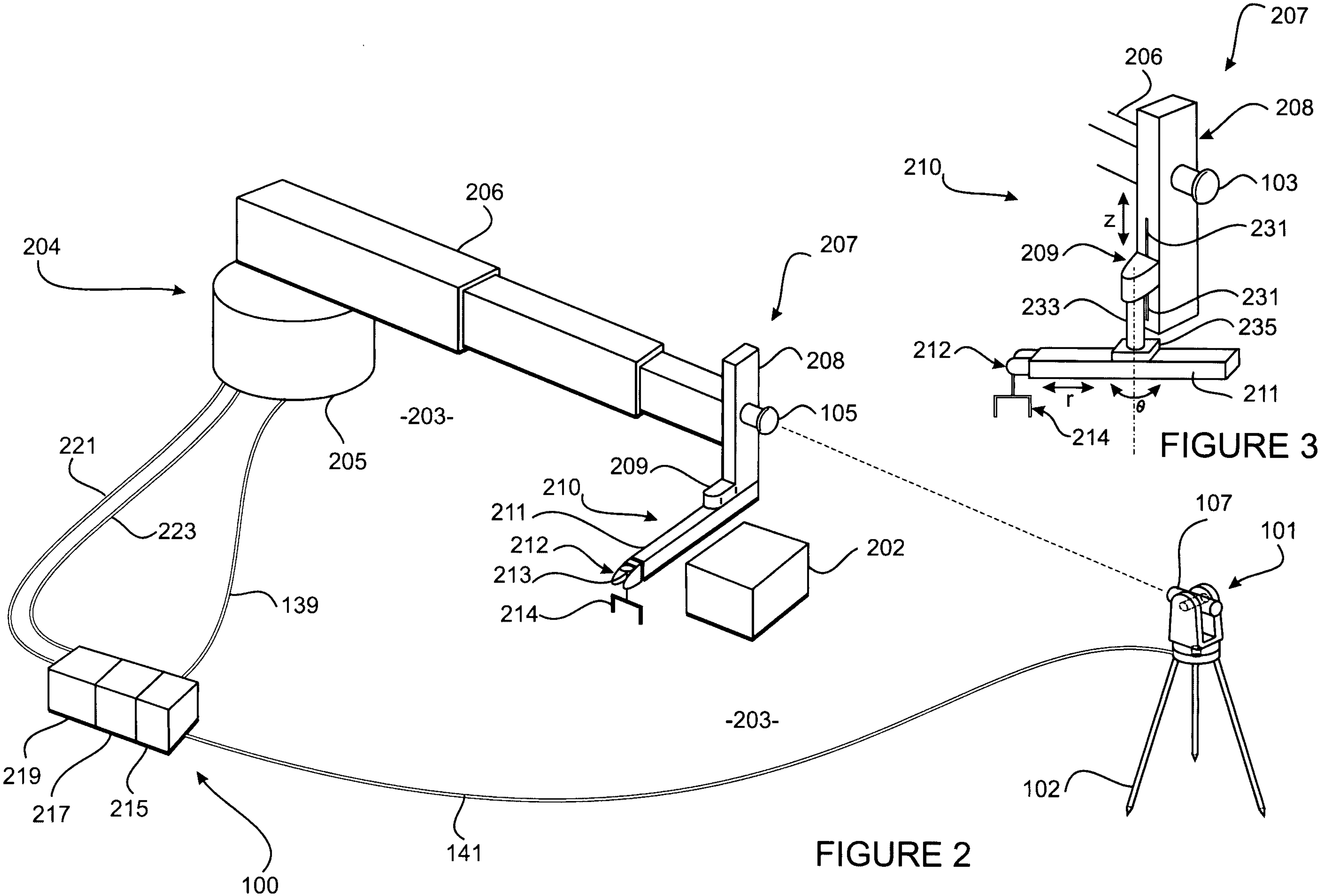

FIGURE 3

FIGURE 2


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FIGURE 2