(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
12 November 2015 (12.11.2015)

WIPO | PCT

(10) International Publication Number
WO 2015/171739 A1

(51) International Patent Classification:
G01B 11/30 (2006.01) *G01N 21/952* (2006.01)
G01N 21/01 (2006.01)

(21) International Application Number:
PCT/US2015/029436

(22) International Filing Date:
6 May 2015 (06.05.2015)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/989,611 7 May 2014 (07.05.2014) US
14/705,056 6 May 2015 (06.05.2015) US

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

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

[Continued on next page]

(54) Title: FIVE AXIS OPTICAL INSPECTION SYSTEM

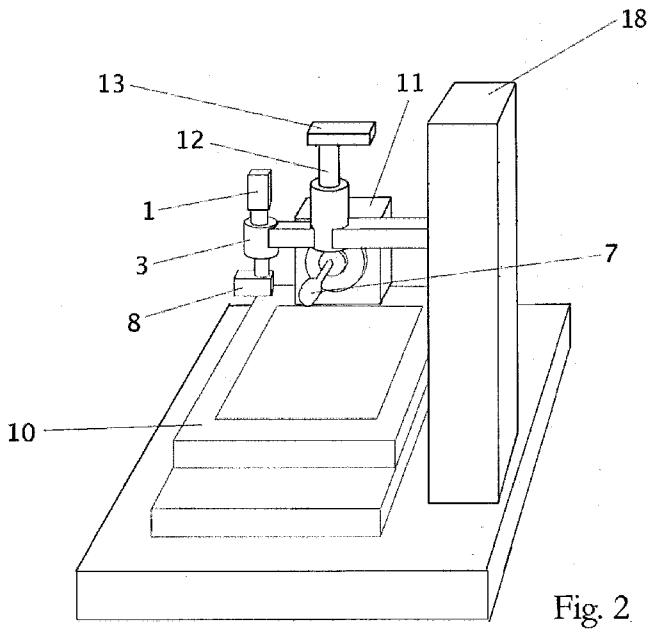

Fig. 2

(57) Abstract: An inspection system that is effective to collect images of a part (7) under inspection. This inspection system includes (a) a three axis linear motion stage (10); (b) a rotary fourth axis stage (11) configured to hold and rotate an object (7) to be inspected. This rotary fourth axis stage (11) is mounted on the three axis linear stage (10); (c) a fifth axis camera (1) and optical system (4) mounted to one of the axes of the three axis linear motion stage (10). This fifth axis camera (1) has an optical axis substantially parallel to the axis of linear motion; (d) a 45 degree mirror (6) configured to bend the optical axis of the fifth axis camera (1) by 90° to point towards the object (7); and (e) a motor (3) configured to rotate the mirror (6) over a range of angles to obtain a fifth axis of viewing orientation.

WO 2015/171739 A1

Published:

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

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

Five Axis Optical Inspection System

For flat parts, like printed circuit boards and silicon wafers, optical inspection systems operate nicely in a three axis configuration. The X and Y axes are used to position the workpiece relative to a camera or a sensor and a Z axis provides focus. The camera used with an optical inspection system needs to be aimed squarely at the feature to be inspected or parallax imaging distortions will cause measurement errors. For workpieces that are generally cylindrical, like a medical stent or a machined piston, mounting the part on a rotary or fourth axis provides the camera with a straight on view of any area of the part. However, when a part has complex contours like, for example, a bullet, obtaining a high resolution image at each point on the surface while aiming the camera normal to a surface patch requires a five axis of motion optical inspection system.

Traditional five axis motion systems used with optical inspection have drawbacks that make them less than ideal. One approach has the part under inspection mounted on a rotary table and then this rotary table is mounted on a second rotary table to obtain the fifth or tilting axis. A drawback is that the amount of mass that the tilting rotary is moving is significantly higher than that of just the part. This makes inspection operations slower than that of a four axis inspection system. It also makes lighting the part for optical inspection more challenging as the mass of the dual rotaries can now preclude convenient placement of lighting components. Five axis motion systems of this type produced by Optical Gauging Products of Rochester, NY, USA and Werth Messtechnik, of Giessen, Germany.

An alternative approach to the fifth tilting axis is to mount the camera and lens components of the inspection system on a rotational stage which is in-turn attached to a Z-axis. One drawback with this approach is that increased mass is added to one of the existing stage axes. A further drawback is that the length of the optical track from object to image at the camera must be accommodated by the stage travel of the system. This can add significant size and cost to the system.

An object disclosed herein is to provide a system to create high-resolution images of parts with complex contours at high speed and with a minimum of stage travel and overall system size. It is a further goal to provide uniform illumination of the object under inspection using both profile and surface illumination.

In accordance with one embodiment, that object is achieved by an inspection system that is effective to collect images of a part under inspection. This inspection system includes (a) a three axis linear motion stage; (b) a rotary fourth axis stage configured to hold and rotate an object to be inspected. This rotary fourth axis stage is mounted on the three axis linear stage; (c) a fifth axis camera and optical system mounted to one of the axes of the three axis linear motion stage. This fifth axis camera has an optical axis substantially parallel to the axis of linear motion; (d) a 45 degree mirror configured to bend the optical axis of the fifth axis camera by 90° to point towards the object; and (e) a motor configured to rotate the mirror over a range of angles to obtain a fifth axis of viewing orientation. In a preferred embodiment, the motor also rotates the lens and camera along with the mirror.

Figure 1 schematically illustrates a fifth axis viewer in accordance with an embodiment disclosed herein.

Figure 2 schematically illustrates a five axis inspection system including the fifth axis viewer of Figure 1.

With reference to Figure 2, the system described herein includes a conventional X,Y,Z three orthogonal axes of motion stage 10. A fourth axis is introduced, as is known from four axis inspection systems, that is driven by a motor 11 mounted on the X or Y stage axis with the part 7. A four axis system is disclosed in United States Patent No. 8,811,691, titled "Stent Inspection System," by Freifeld.

A key feature of the present embodiment is to locate the optical axis of the lens and camera 1 for viewing part 7 features mounted as is commonly found on traditional machines on the Z-axis 18 with the optical axis substantially parallel to the Z-axis 18. Referring now to Figure 1, a computer numerically controlled right angle reflector 15 is then utilized to bend the traditionally downward facing optical axis 16 by 90 degrees and a motor 3 to drive this right angle beam splitter cube 6 to point outward to the part 7.

In one preferred embodiment the entire camera 1, lens 4 and right angle reflector 15 are all rotated by the fifth axis of motion motor 3 about the primary optical axis 16. The immediate advantage of this method is that the mass of the reflector 15 and, optionally, the mass of the lens 4 and camera 1 are being rotated about their own center of mass thus keeping the moment inertia to a minimum and the space taken in the system stage layout to a minimum as well. This allows for high-speed motion with fast

mechanical settling times. The entire package size of this fifth axis configuration can be minimized mechanically by configuring the optical axis 16 to be on center and within the fifth axis motor 3, so long as a motor 3 with a hollow shaft 19 of sufficient diameter to allow the full optical path of the system to propagate without vignetting is provided. If the lens 4 is telecentric, the optical system is well disposed for gauging applications.

By using a cube beamsplitter 6 to provide the 90 degree redirection of the optical axis 16, illumination can be introduced to the part through the beamsplitter 6 with the right angle reflector 15 being a partially reflective mirror. Introducing bright field illumination via light source 5 has advantages over traditional epi-illumination or through the objective lens surface illumination. First, this simplifies the optical configuration. In the more traditional configuration a beamsplitter cube must be placed in a collimated space between the first lens objective and a camera relay lens. This increases the size and complexity of the optical system and tends to introduce stray illumination into the camera, softening the image. Moreover, illumination introduced at the beamsplitter cube below the primary objective can cover a wider angle of illumination as it is not limited by the coverage angle as defined by the numerical aperture of the lens. This can provide a more broadly illuminated object improving image quality. Adding a ring light 9 in front of the beam splitter 6 as a dark field source of illumination can provide an especially broad coverage of illumination. Alternatively, if light is not desired to be directed onto the part from behind the beamsplitter 6, a simple mirror instead of a more elaborate beam splitter cube. The two light sources on either side of the partially reflecting mirror can be operated either individually or simultaneously to create a large area of combined dark and bright field illumination coverage

With reference back to Figure 2, a further approach is to add a large area camera 13 and lens 12 to obtain a rotational or a flat scan of the part 7 under inspection. For parts that are generally rotationally symmetric it is especially advantageous if the large area camera 13 is a line scan camera. From these large area views the positions of features to be inspected by the fifth axis camera 1 can be more easily determined in spatial coordinates then strictly by driving the fifth axis through a series of predetermined computer numerically controlled moves. This is especially helpful when inspecting parts that are not completely rigid as features are not always where one might expect them based on their design model.

Figure 1 schematically illustrates a fifth axis viewer. A camera 1 views an object 7 through a tube 2, a lens 4 and finally a beamsplitter cube 6. In this embodiment the entire optical system is rotated about a portion of the optical axis 16 by motor 3. The viewer module 8 has an internal light source 5 positioned so its light shines through the beamsplitter cube 6 and onto the object 7 under inspection. A ring light 9 is added in front of the beam splitter cube so that its light also hits the object 7.

Figure 2 schematically illustrates a full view of a five axis inspection system containing the right angle fifth axis viewer 8 driven by a rotating motor 3 to capture images of object 7 in any angular orientation by camera 1. The part 7 under inspection is mounted on a rotary motor stage 11, the fourth axis of the system, which in turn is mounted to a three axis linear positioning stage 10. The system also contains a lens 12 having an extended depth of focus of 5mm or more that is used for taking flat or rotational large area images of the part 7 using a line scan camera 13.

In an embodiment, the inspection system includes a digital camera and a lens defining an optical axis. There is a partial mirror below, the lens redirecting the optical axis 90 degrees to view an object. An extended area light source is placed behind and configured to direct light through said partial mirror to provided extended bright field illumination on said object with a broad angle of coverage. The inspection system light source includes light emitting diodes and the partial mirror is a beam splitter cube.

What is claimed:

1. An inspection system effective to collect images of a part 7 under inspection, characterized by:
   a) a three axis linear motion stage 10;
   b) a rotary fourth axis stage 11 configured to hold and rotate an object 7 to be inspected, said rotary fourth axis stage 11 mounted on said three axis linear stage 10;
   c) a fifth axis camera 1 and optical system 8 mounted to one of the axes of the three axis linear motion stage 10, said fifth axis camera 13 having an optical axis substantially parallel to this axis of linear motion;
   d) a 45 degree mirror configured to bend said optical axis of the fifth axis camera by 90° to point towards said object 7; and
   e) a motor 3 configured to rotate the mirror over a range of angles to obtain a fifth axis of viewing orientation.

2. The inspection system of claim 1 characterized in that said motor 3 also rotates the entire fifth axis optical system 8.

3. The inspection system of claim 1 characterized in that the 45 degree mirror is a partially reflecting mirror 6 and a light source 5 is placed on one side of the partially reflecting mirror 6 substantially perpendicular to the first optical axis so that the light from the light source 6 is directed as bright field illumination at the object 7 under inspection.

4. The inspection system of claim 3 characterized in that a second light source 9 is a ring light source capable of illuminating said object 7 placed in front of said 45 degree mirror 6 with the turned optical viewing axis directed through the center of the ring light source 9 acting as a dark field source of illumination.

5. The inspection system of claim 4 characterized in that the two light sources 5, 9 on either side of the partially reflecting mirror 6 can be operated either individually or simultaneously to create a large area of combined dark and bright field illumination coverage.

6. The optical system of claim 1 characterized in that the fifth axis optical system 8 utilizes a telecentric design.

7. The inspection system of claim 1 further characterized in that a large format camera 13 viewing the object 7 through a large format lens 12 mounted on one axis of the three axis linear motion stage 10, the large format camera 13 configured to capture large area images of the object 7 under inspection and to direct the fifth axis camera 1 to specific feature locations on said object 7 based on found feature locations within the large format image.

8. The inspection system of claim 6 characterized in that the large format camera 1 is a line scan camera.

9. The inspection system of claim 6 characterized in that the large format lens 12 utilizes a telecentric design with an extended depth of focus of at least 5mm.

10. An inspection system characterized by:

a digital camera 1 and lens 4 defining an optical axis;

a partial mirror 6 below, said lens 6 redirecting said optical axis 90 degrees to view an object 7;

an extended area light source 5, 9 is placed behind and configured to direct light through said partial mirror 6 to provided extended bright field illumination on said object 7 with a broad angle of coverage.

11. The inspection system of claim 10 characterized in that said light source 5, 9 includes light emitting diodes 9.

12. The inspection system of claim 10 characterized in that said partial mirror 6 is a beam splitter cube.

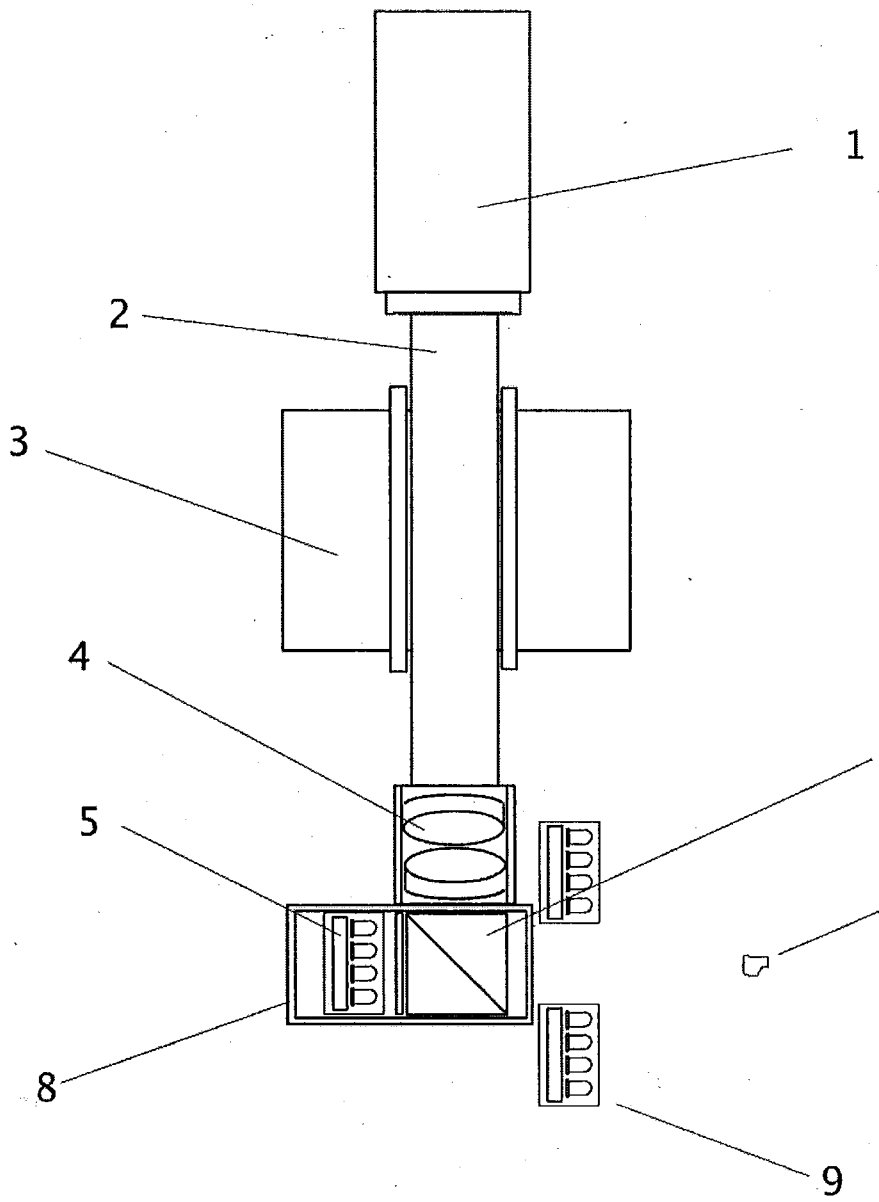

Fig. 1

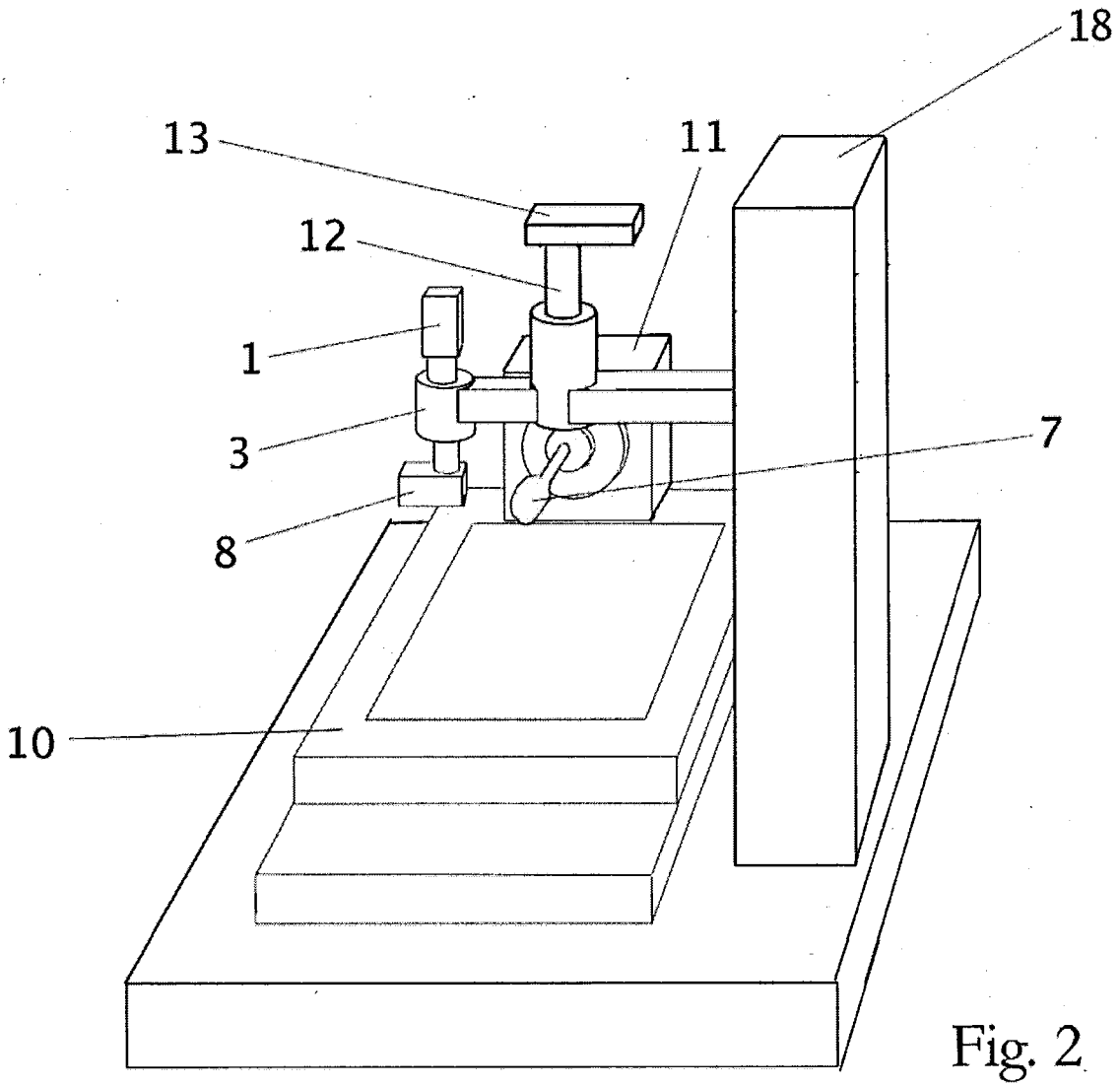

Fig. 2

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US15/29436

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

See additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:
1-9

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US15/29436

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G01B 11/30; G01N 21/01, 21/952 (2015.01)
CPC - A61F 2240/008; G01N 21/8806 2021/8825
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8): G01B 9/00, 9/04, 9/08, 11/02, 11/24, 11/30; G01N 21/00, 21/01, 21/88, 21/952, 21/954, 21/956 (2015.01); CPC: A61F 2240/008; G01N 21/01, 21/88, 21/8803, 21/8806, 2021/8822, 2021/8825, 2021/8841, 21/8851, 21/952; G01B 9/04, 9/08, 11/02, 11/24, 11/30

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); ProQuest (Derwent, INSPEC, NTIS, PASCAL, Current Contents Search, Dissertation Abstracts Online, Inside Conferences); EBSCO Discovery Service; Google Scholar; KEYWORDS: inspect, imag, camera, stage, stent, axis, dark field, bright field, line camera, telecentric, lens depth, focus, mirror

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X --- Y	US 2010/0014747 A1 (FREIFELD, D) January 21, 2010; abstract; figures 1-8; paragraphs [0010, 0026-0034, 0057]	1, 2, 7, and 8 --- 3-6 and 9
Y	US 6,667,762 B1 (BOUVIER, W et al.) December 23, 2003; figures 1, 5, and 11; column 4, lines 8-25; column 6, lines 25-29; column 11, lines 18-45	3-5
Y	US 2011/0007151 A1 (GOLDBERG, D) January 13, 2011; figure 3; paragraphs [0050 and 0120]	6 and 9
A	US 2010/0309307 A1 (JIN, J) December 9, 2010; entire document	1-9
A	US 2010/0262230 A1 (VECERINA, I et al.) October 14, 2010; entire document	1-9
A	WO 03/046632 A1 (VR INTERACTIVE CORPORATION) June 5, 2003; entire document	1-9

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent 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	Date of mailing of the international search report
11 September 2015 (11.09.2015)	06 OCT 2015
Name and mailing address of the ISA/ Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Shane Thomas PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/US15/29436

-***-Continued from Box III: Observations where unity of invention is lacking-***-

This application contains the following inventions or groups of inventions which are not so linked as to form a single general inventive concept under PCT Rule 13.1. In order for all inventions to be examined, the appropriate additional examination fee must be paid.

Group I: Claims 1-9 are directed toward an inspection system effective to collect images of a part under inspection, a three axis linear motion stage, a rotary fourth axis stage configured to hold and rotate an object to be inspected, a fifth axis camera and optical system mounted to one of the axes of the three axis linear motion stage, said fifth axis camera having an optical axis substantially parallel to this axis of linear motion;a 45 degree mirror configured to bend said optical axis of the fifth axis camera by 90° to point towards said object, a motor configured to rotate the mirror over a range of angles to obtain a fifth axis of viewing orientation.

Group II: Claims 10-12 are directed toward an inspection system comprising a digital camera and lens defining an optical axis, a partial mirror below, said lens redirecting said optical axis 90 degrees to view an object, an extended area light source is placed behind and configured to direct light through said partial mirror to provided extended bright field illumination on said object with a broad angle of coverage.

The inventions listed as Groups I and II do not relate to a single general inventive concept under PCT Rule 13.1 because, under PCT Rule 13.2, they lack the same or corresponding special technical features. Group I has at least a three axis linear motion stage,a rotary fourth axis stage configured to hold and rotate an object to be inspected, said rotary fourth axis stage mounted on said three axis linear stage, a fifth axis camera and optical system mounted to one of the axes of the three axis linear motion stage, said fifth axis camera having an optical axis substantially parallel to this axis of linear motion, a 45 degree mirror configured to bend said optical axis of the fifth axis camera by 90° to point towards said object, a motor configured to rotate the mirror over a range of angles to obtain a fifth axis of viewing orientation that Group II does not have. Group II has at least an extended area light source is placed behind and configured to direct light through said partial mirror to provided extended bright field illumination on said object with a broad angle of coverage that Group I does not have.

The common technical features of Groups I and II are at least a camera, optical system, optical axis, a mirror redirecting optical axis 90 degrees to view object. This common feature is disclosed by WO 03/046632 A1 to VR INTERACTIVE CORPORATION (hereinafter 'VR Interactive'). VR Interactive discloses a camera (camera 35, figures 1 and 2, page 10, lines 33-35), optical axis (optical axis of the primary mirror for focussing and viewing, figures 1 and 2, page 10, lines 31-35), a mirror redirecting optical axis 90 degrees to view object (redirecting light at 90 degrees to the optical axis of the primary mirror for focusing and viewing, figures 1, 2, 7, and 9, page 4, lines 8-13, page 10, lines 29-35).

Since the common technical feature is previously disclosed by the VR reference, these common features are not special and so Groups I and II lack unity.