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(54) DEVICE AND METHOD FOR ASSISTING LAPAROSCOPIC SURGERY - DIRECTING AND MANEUVERING ARTICULATING TOOL

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(21) Appl. No.: **14/671,128**

(22) Filed: **Mar. 27, 2015**

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(60) Provisional application No. 61/707,976, filed on Sep. 30, 2012, provisional application No. 61/973,899, filed on Apr. 2, 2014, provisional application No. 62/130,641, filed on Mar. 10, 2015.

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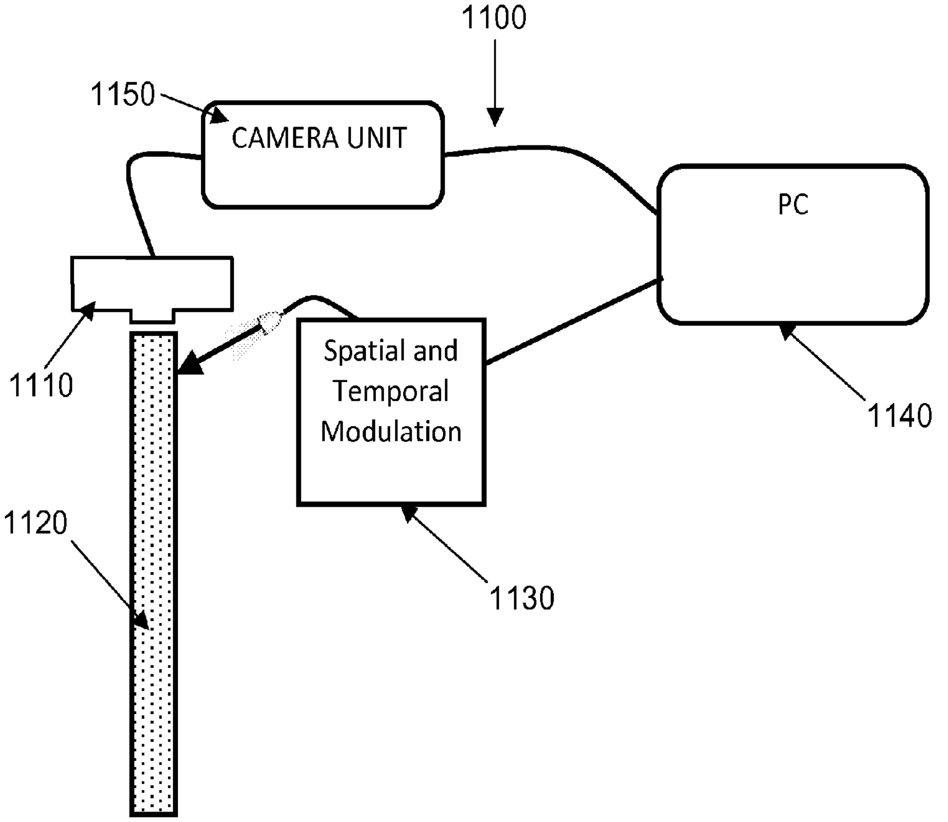
A61B 1/06	(2006.01)
A61B 17/00	(2006.01)
A61B 1/04	(2006.01)

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

CPC ***A61B 19/5244*** (2013.01); ***A61B 19/20*** (2013.01); ***A61B 19/2203*** (2013.01); ***A61B 17/00234*** (2013.01); ***A61B 1/042*** (2013.01); ***A61B 1/0661*** (2013.01); ***A61B 1/00009*** (2013.01); ***A61B 19/56*** (2013.01); ***A61B 1/00016*** (2013.01); *A61B 2019/2215* (2013.01); *A61B 2019/5257* (2013.01); *A61B 2019/5265* (2013.01); *A61B 2560/0233* (2013.01); *A61B 2560/0475* (2013.01); *A61B 2019/5295* (2013.01); *A61B 2019/5274* (2013.01); *A61B 2017/00296* (2013.01)

(57) ABSTRACT

A surgical controlling system that includes: a surgical tool that is insertable into a surgical environment of a human body for a surgical procedure. Logic configured to locate in real-time the 3D spatial position of the at least one surgical tool at any given time t. The system also includes at least one movement detector and a controller in communication with a controller database.



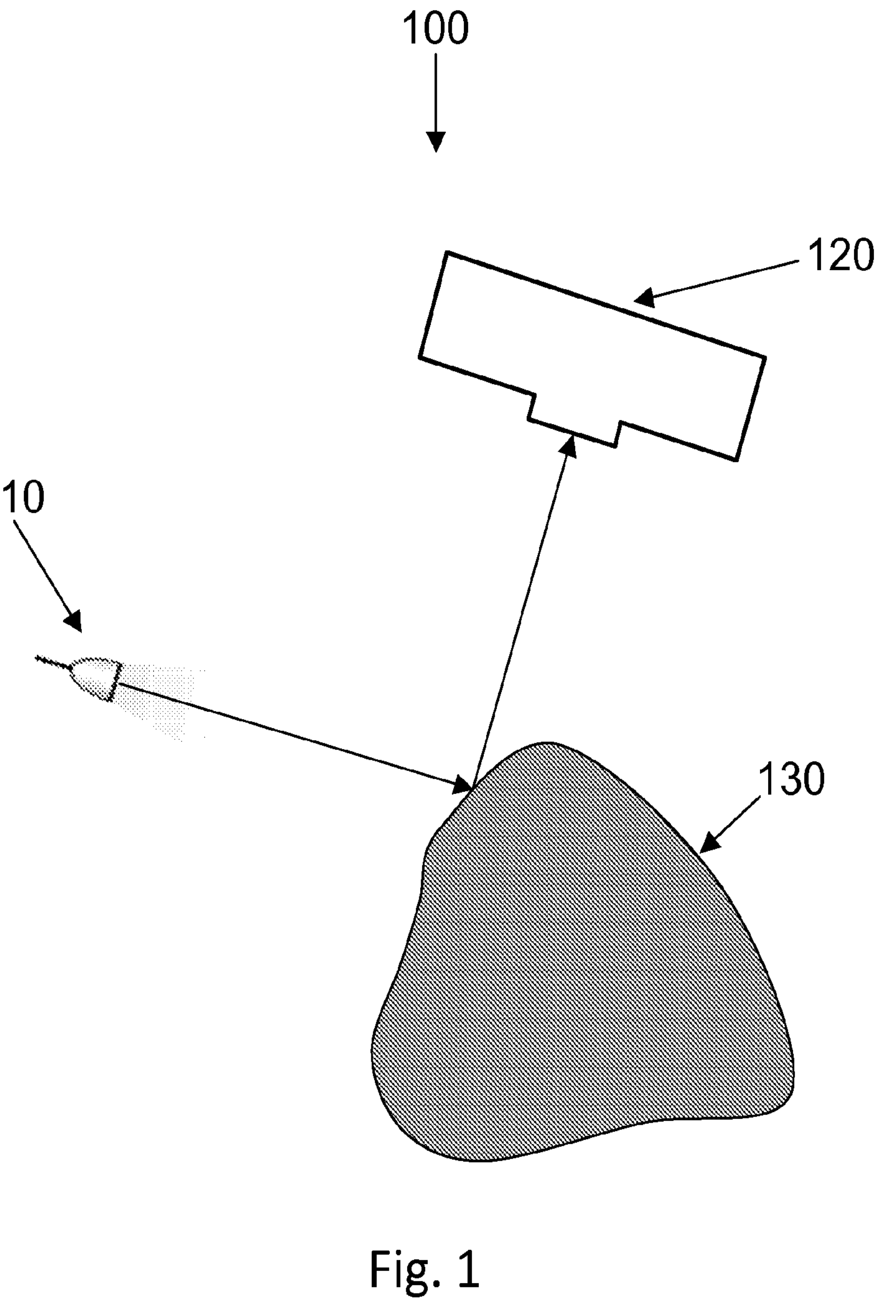


Fig. 1

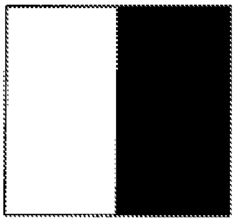


FIG. 2A (HSB)

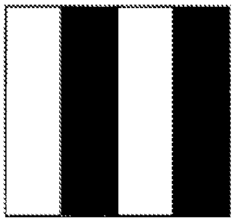


FIG. 2B

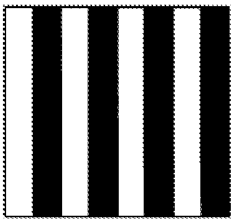


FIG. 2C

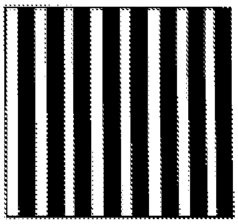


FIG. 2D

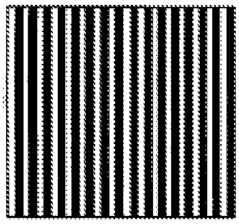


FIG. 2E

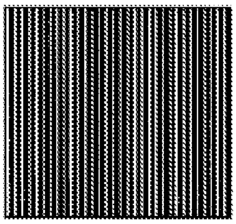


FIG. 2F

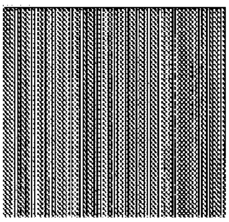


FIG. 2G

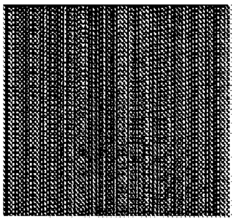


FIG. 2H (LSB)

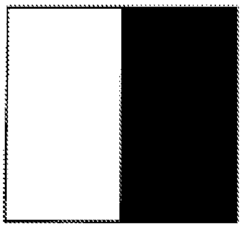


FIG. 3A (HSB)

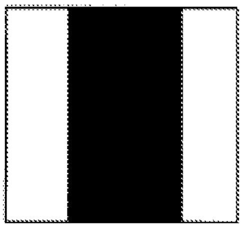


FIG. 3B

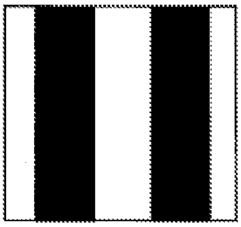


FIG. 3C

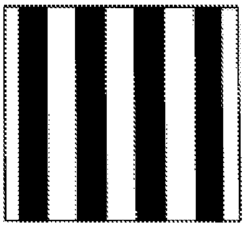


FIG. 3D

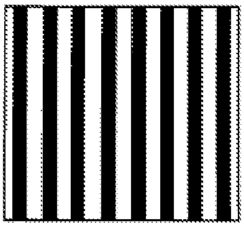


FIG. 3E

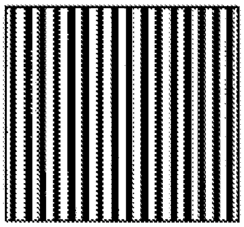


FIG. 3F

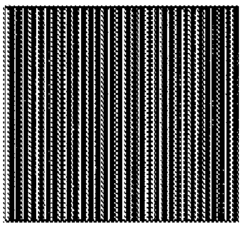


FIG. 3G

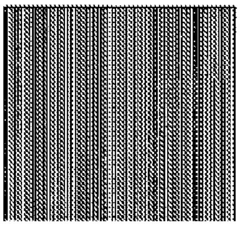


FIG. 3H(LSB)

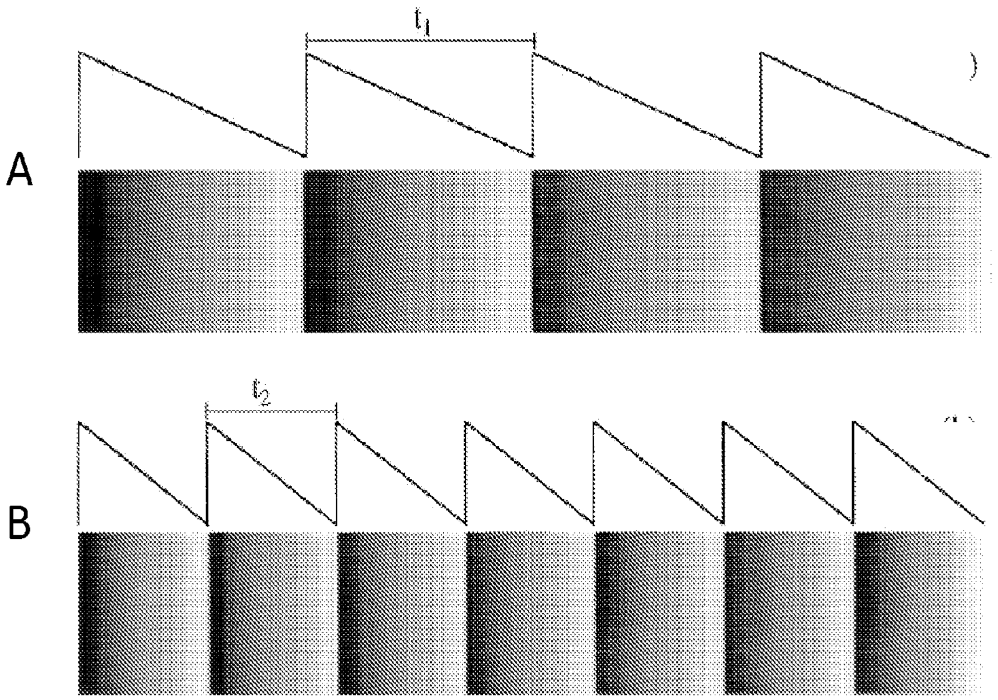

t1
A
t2
B

Fig. 4

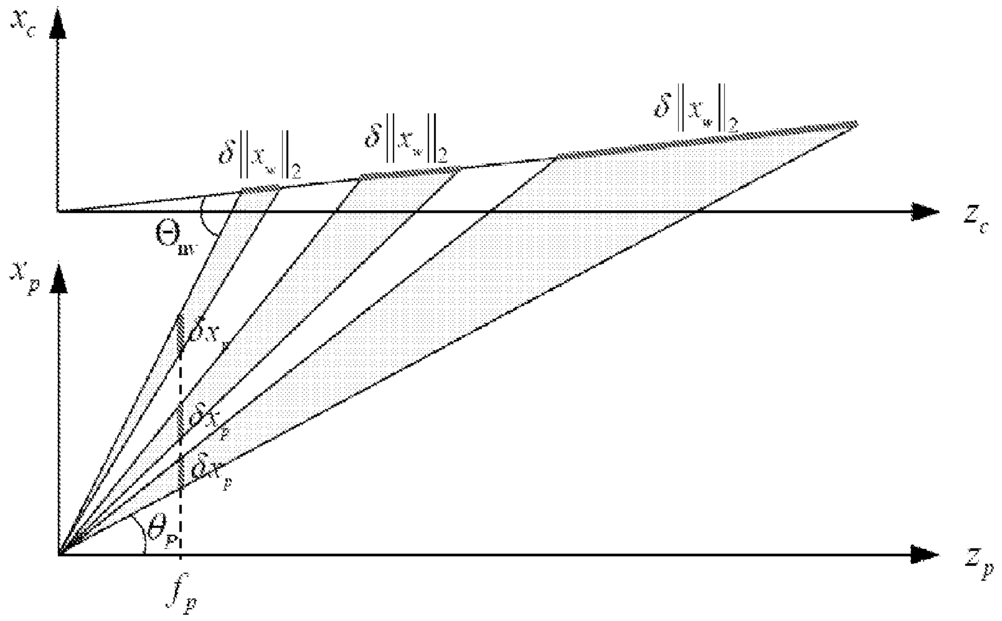

x_c
$\delta\|x_w\|_2$
$\delta\|x_w\|_2$
$\delta\|x_w\|_2$
z_c
Θ_{uv}
x_p
δx_p
δx_p
δx_p
θ_p
z_p
f_p

Fig. 5

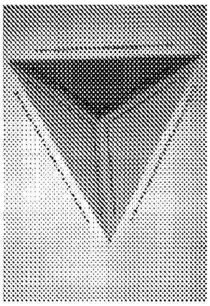


Fig. 6A

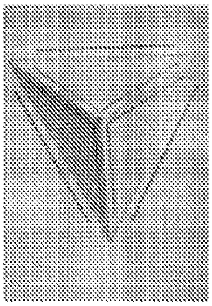


Fig. 6B

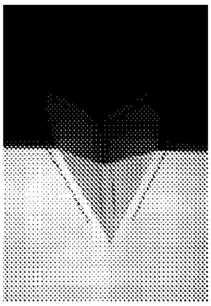


Fig. 6C

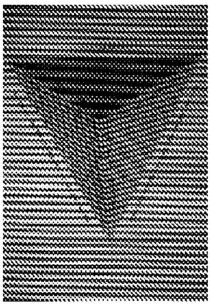


Fig. 6D

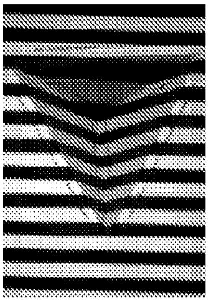


Fig. 7A

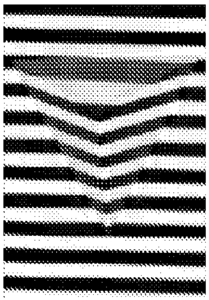


Fig. 7B

Fig. 7C

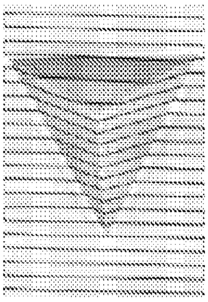


Fig. 7D

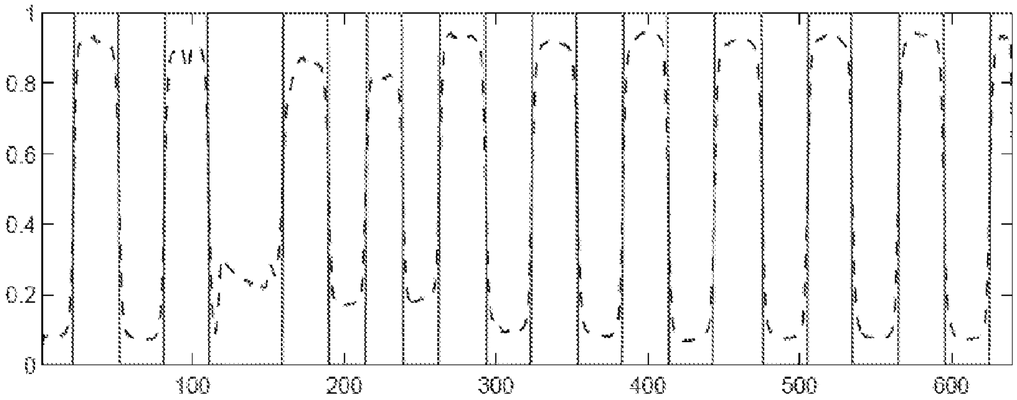


Fig. 7E

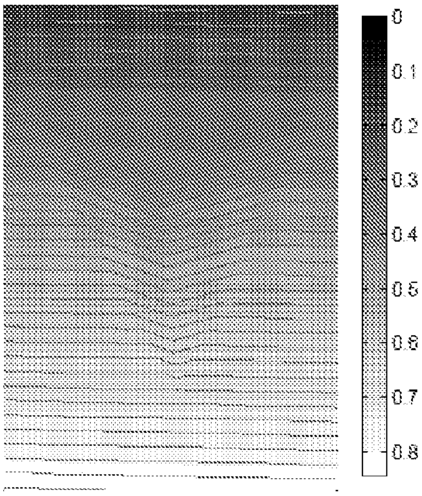


FIG. 8A

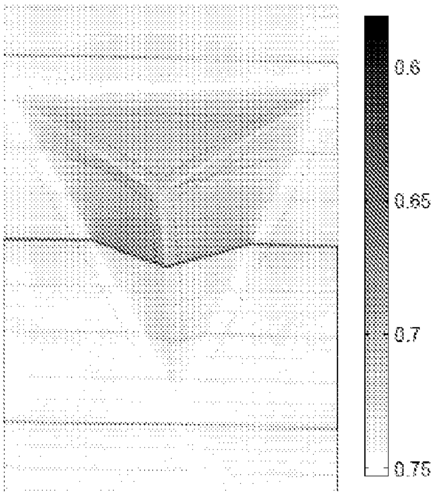


FIG. 8B

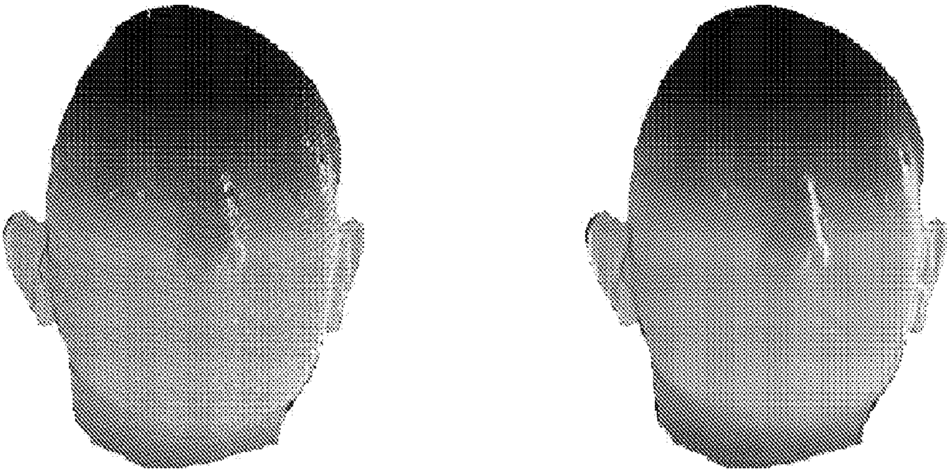


Fig. 9

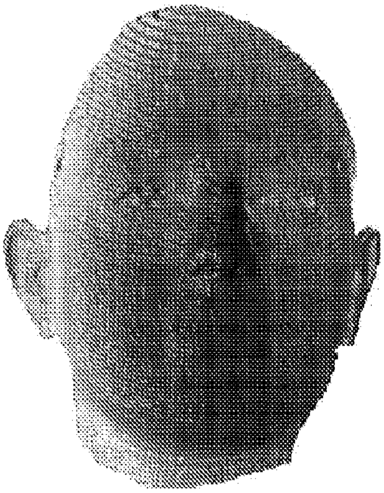


FIG. 10A

FIG. 10B

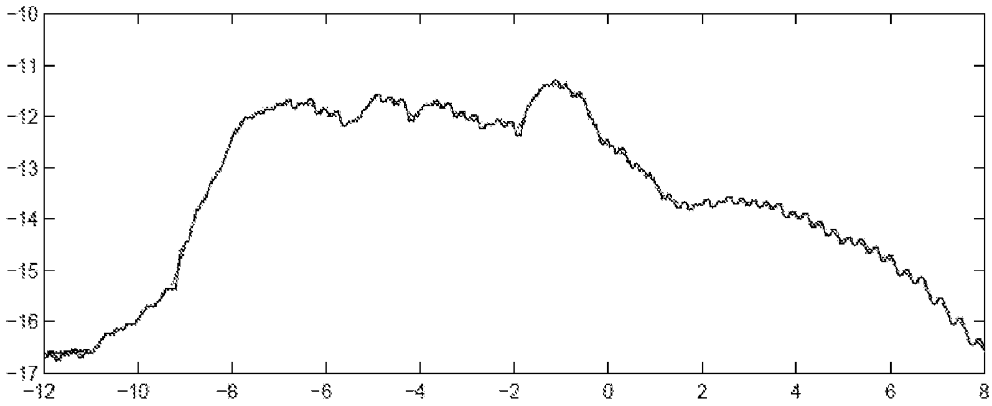


FIG. 10C

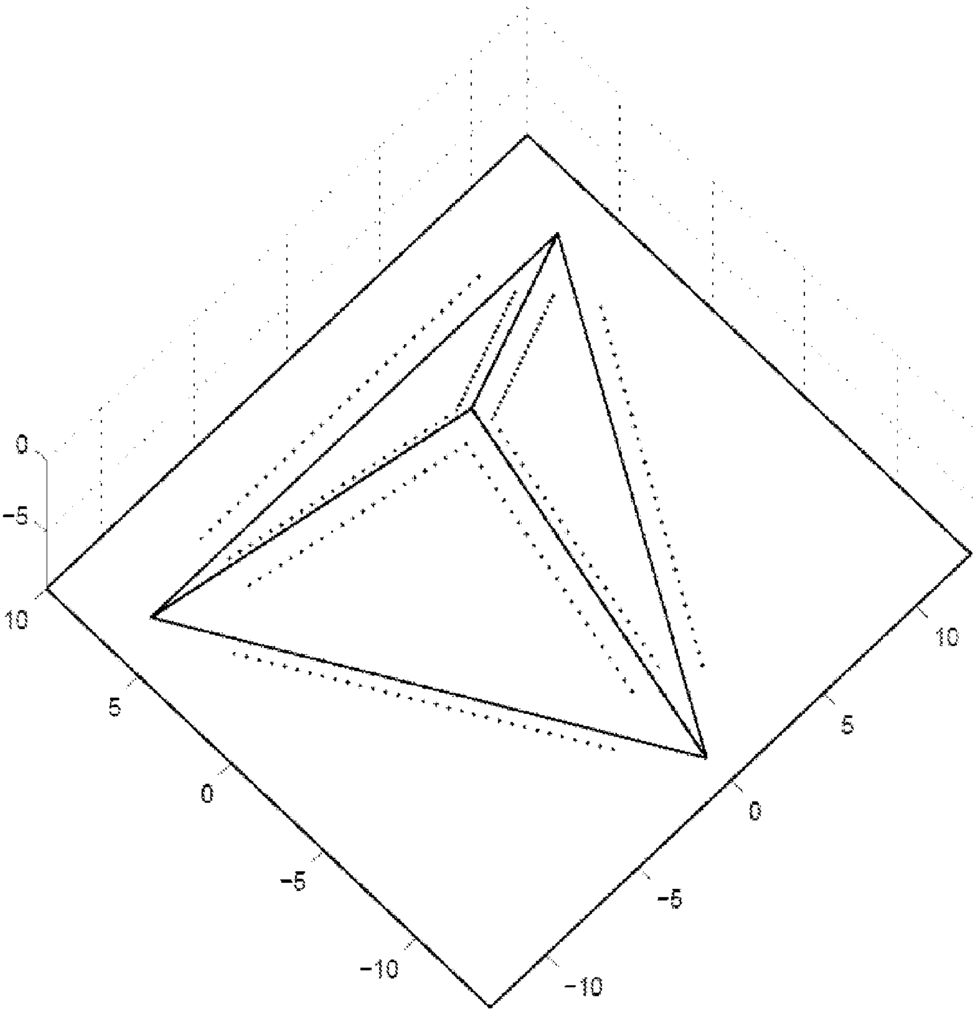


Fig. 11

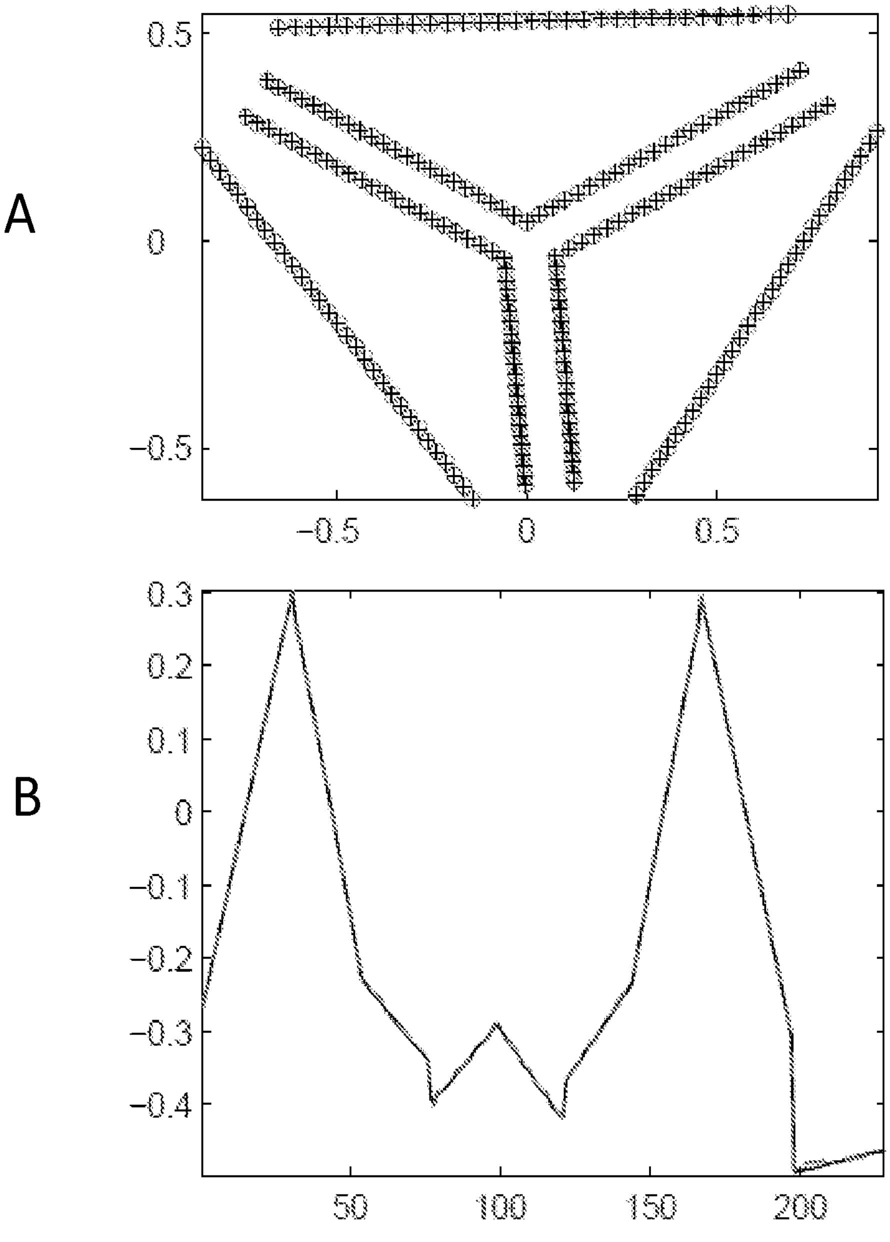


Fig. 12

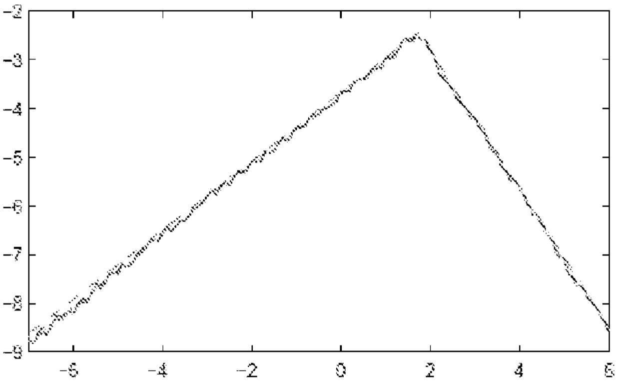


FIG. 13A

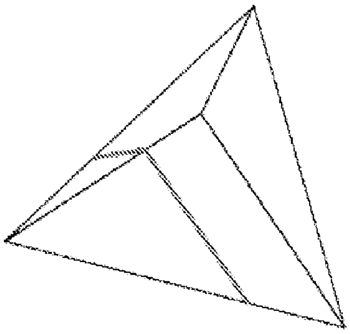


FIG. 13B

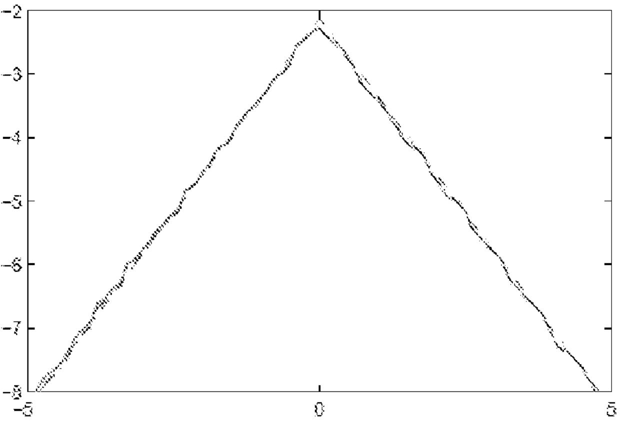


FIG. 13C

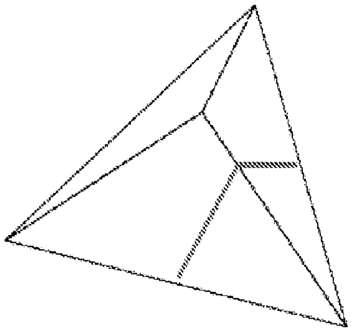


FIG. 13D

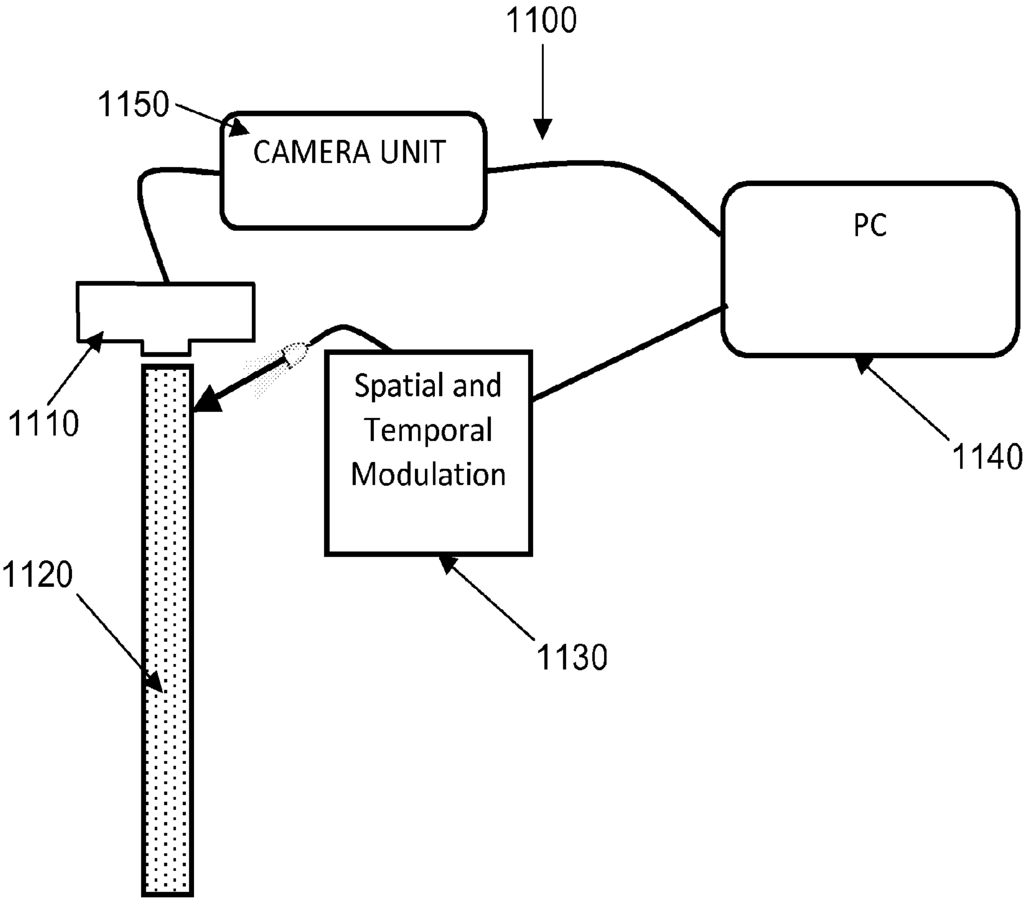

1100
1150
CAMERA UNIT
PC
1110
Spatial and Temporal Modulation
1140
1120
1130

Fig. 14

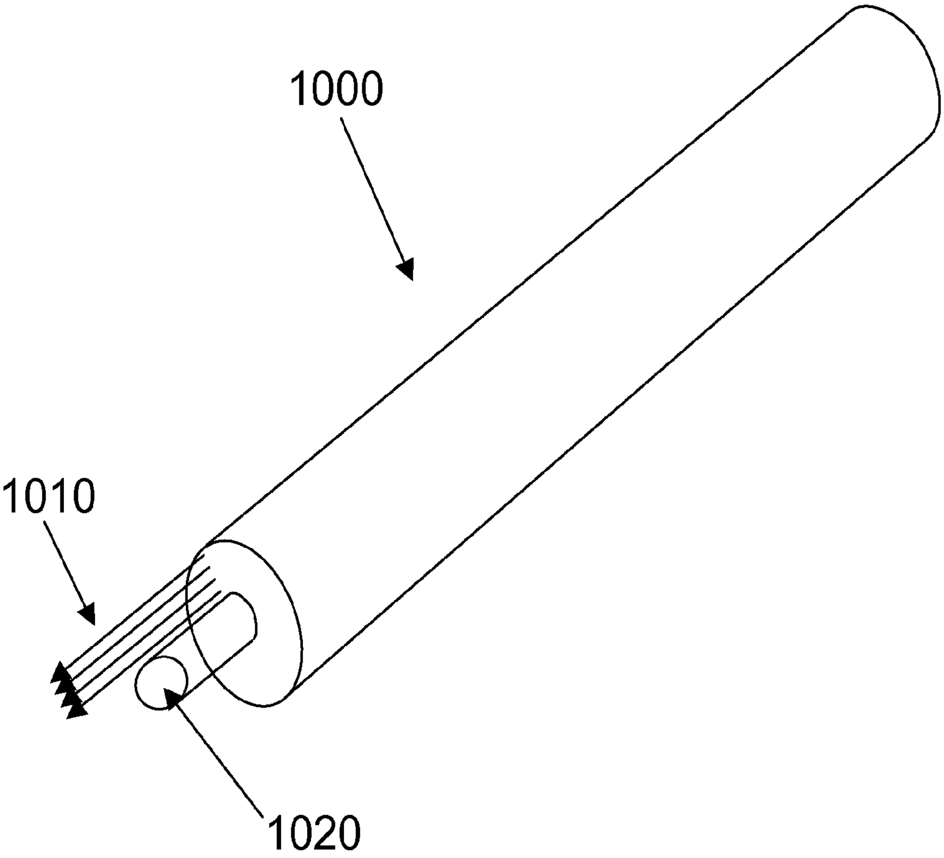


Fig. 15

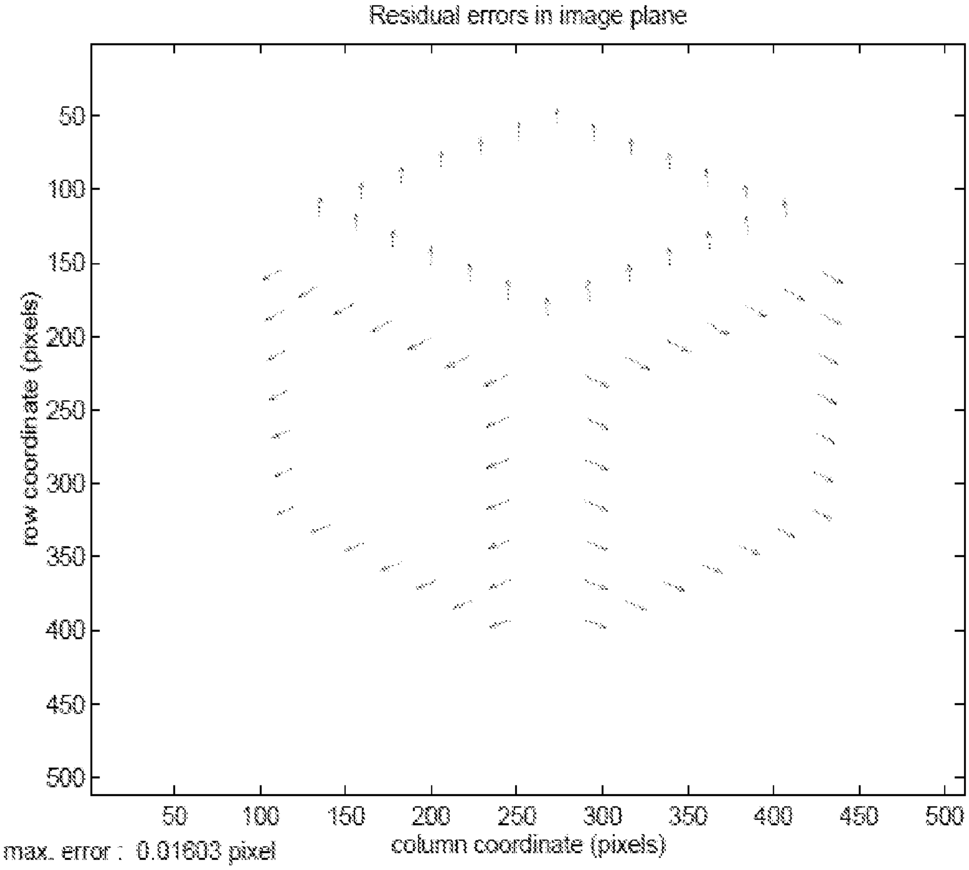

Residual errors in image plane
row coordinate (pixels)
50
100
150
200
250
300
350
400
450
500
column coordinate (pixels)
50
100
150
200
250
300
350
400
450
500
max. error : 0.01603 pixel

Fig. 16

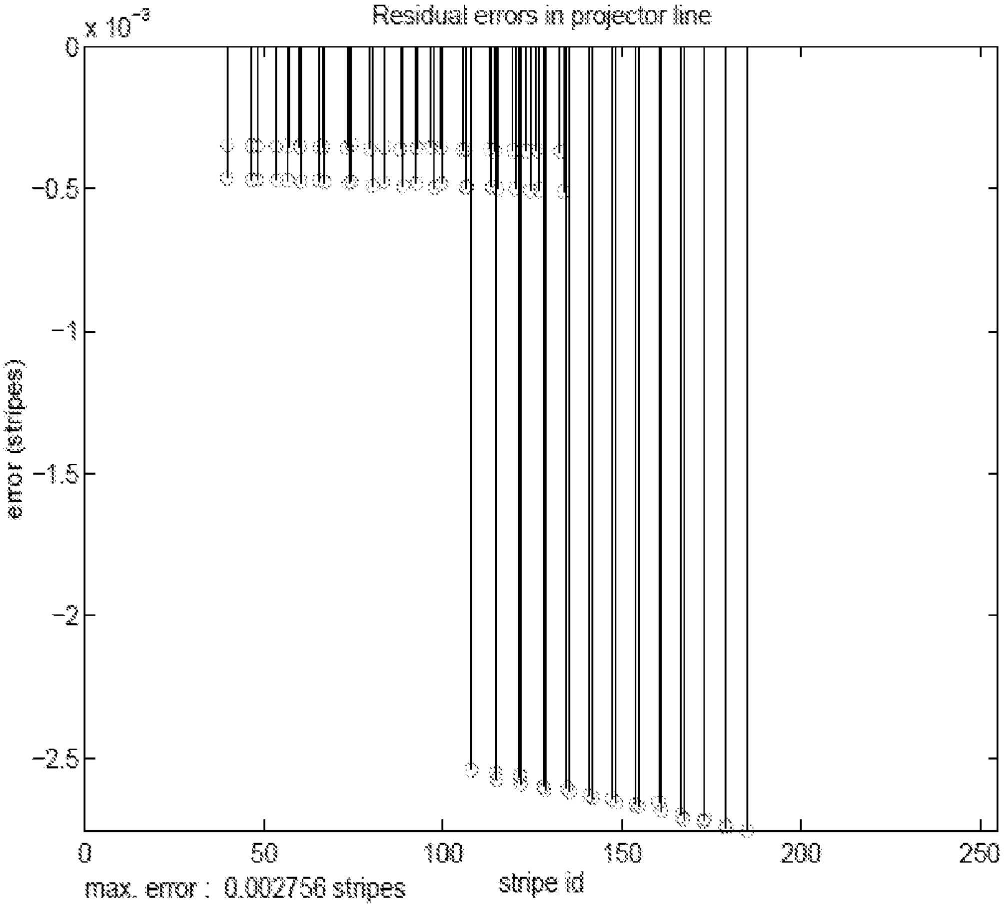

Residual errors in projector line
x 10^-3
0
−0.5
−1
−1.5
−2
−2.5
error (stripes)
0
50
100
150
200
250
stripe id
max. error : 0.002756 stripes

Fig. 17

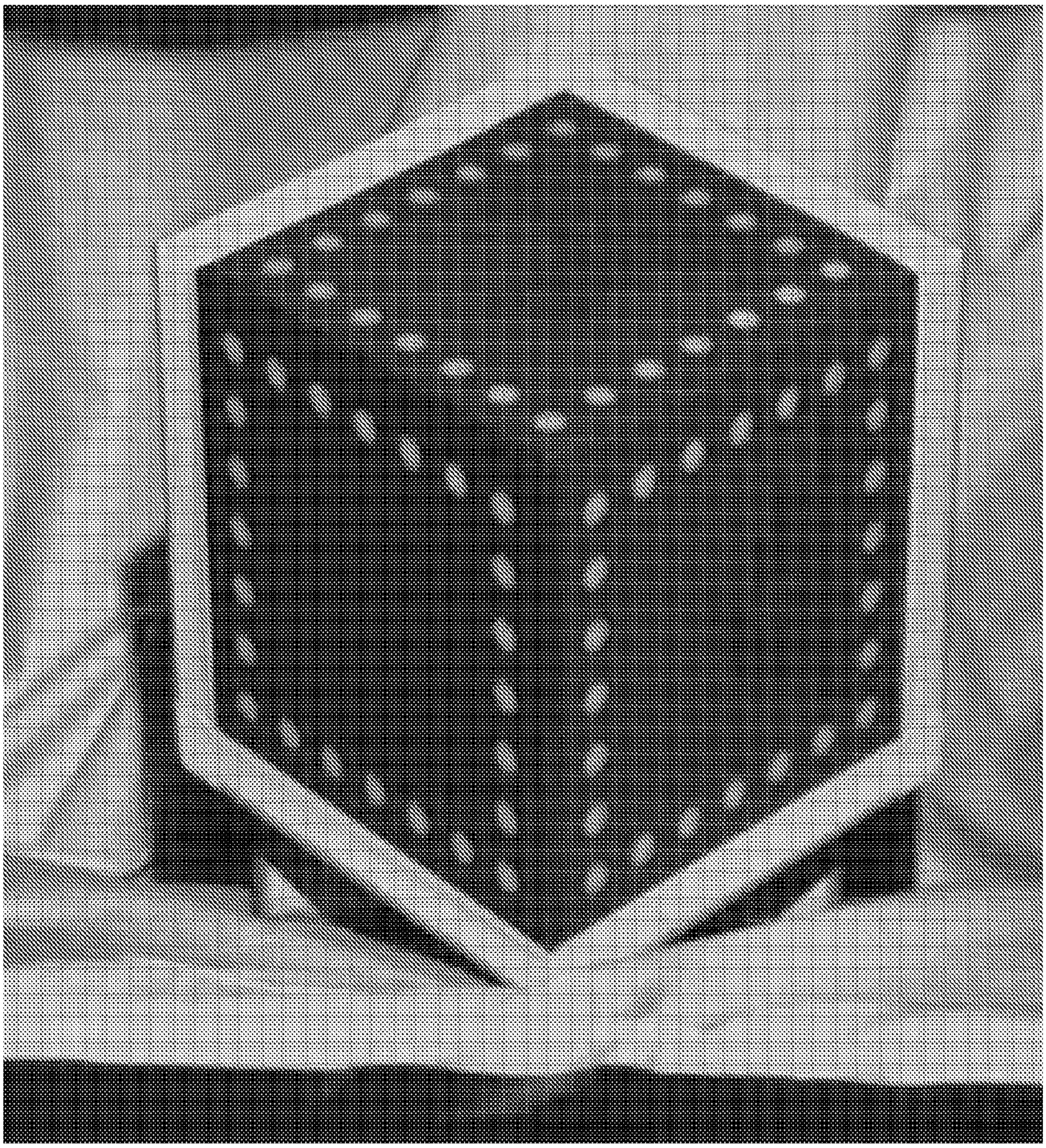


Fig. 18

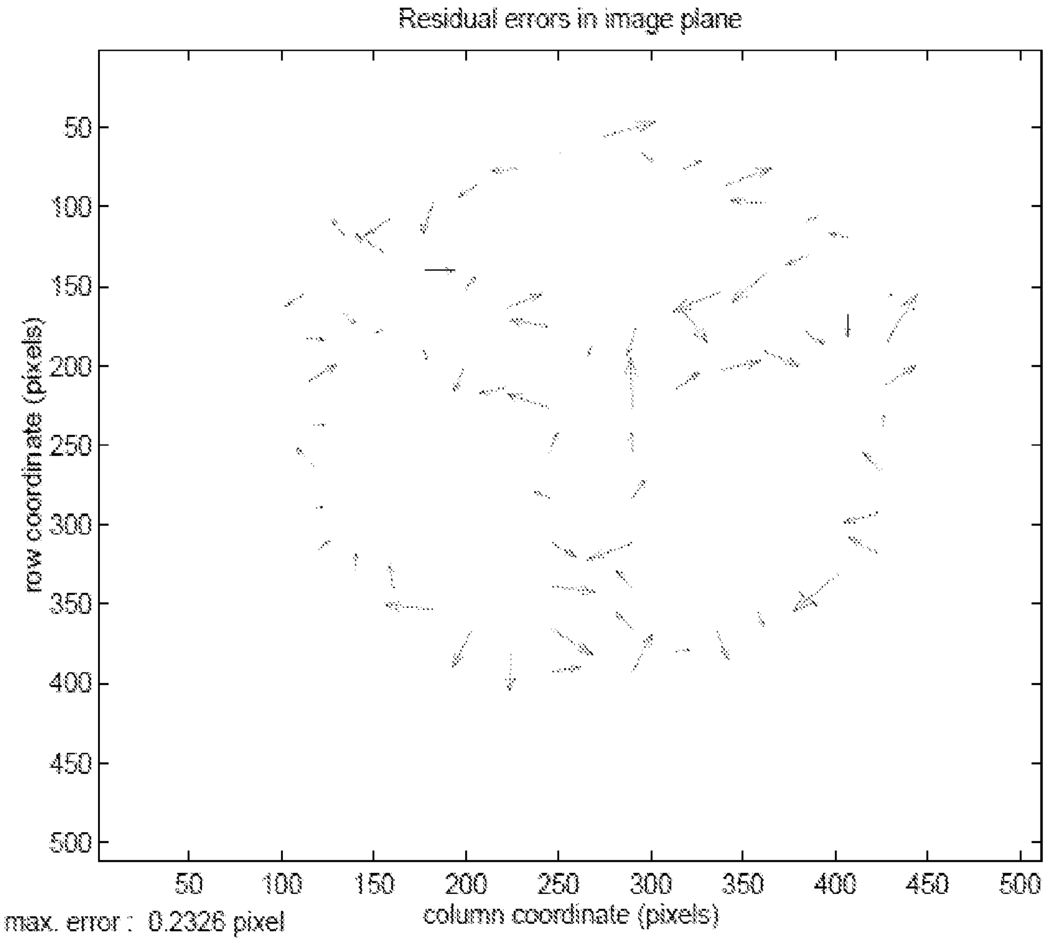

Residual errors in image plane
row coordinate (pixels)
50
100
150
200
250
300
350
400
450
500
column coordinate (pixels)
50
100
150
200
250
300
350
400
450
500
max. error : 0.2326 pixel

Fig. 19

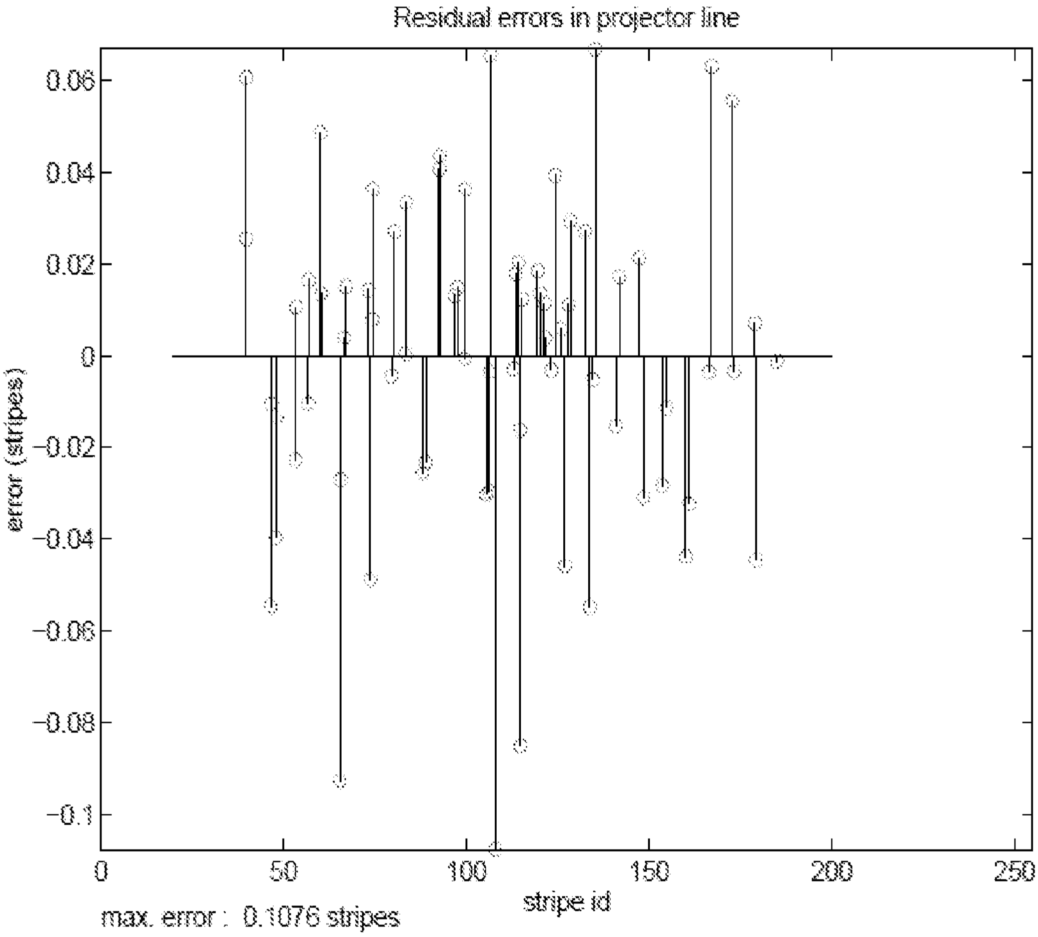

Residual errors in projector line
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
error (stripes)
0
50
100
150
200
250
stripe id
max. error : 0.1076 stripes

Fig. 20

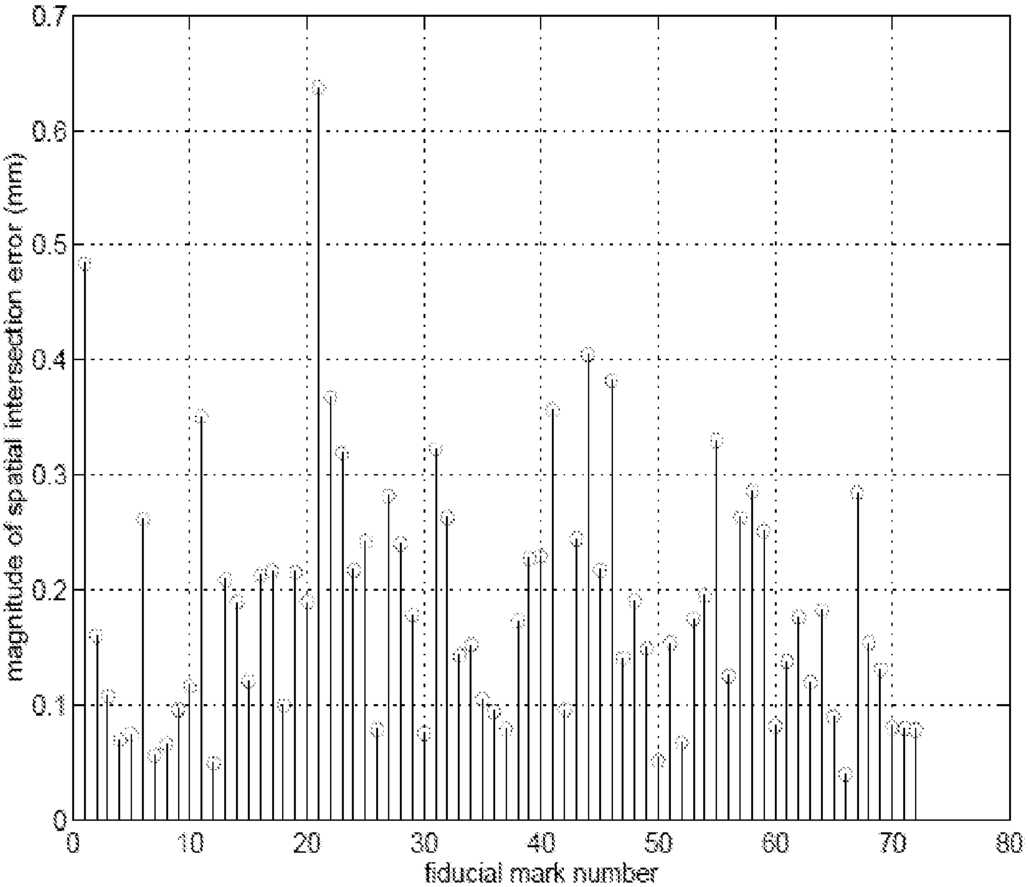

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
magnitude of spatial intersection error (mm)
0
10
20
30
40
50
60
70
80
fiducial mark number

Fig. 21

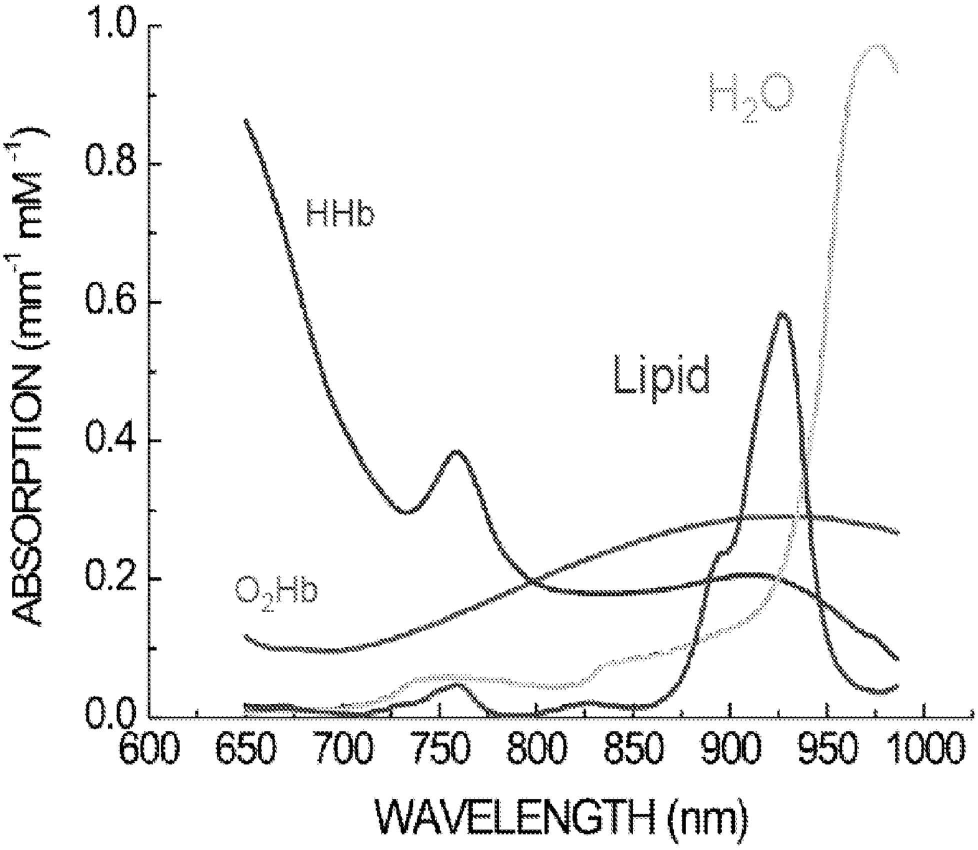

1.0
0.8
0.6
0.4
0.2
0.0
ABSORPTION (mm^{-1} mM^{-1})
600
650
700
750
800
850
900
950
1000
WAVELENGTH (nm)
HHb
H_2O
Lipid
O_2Hb

Fig. 22

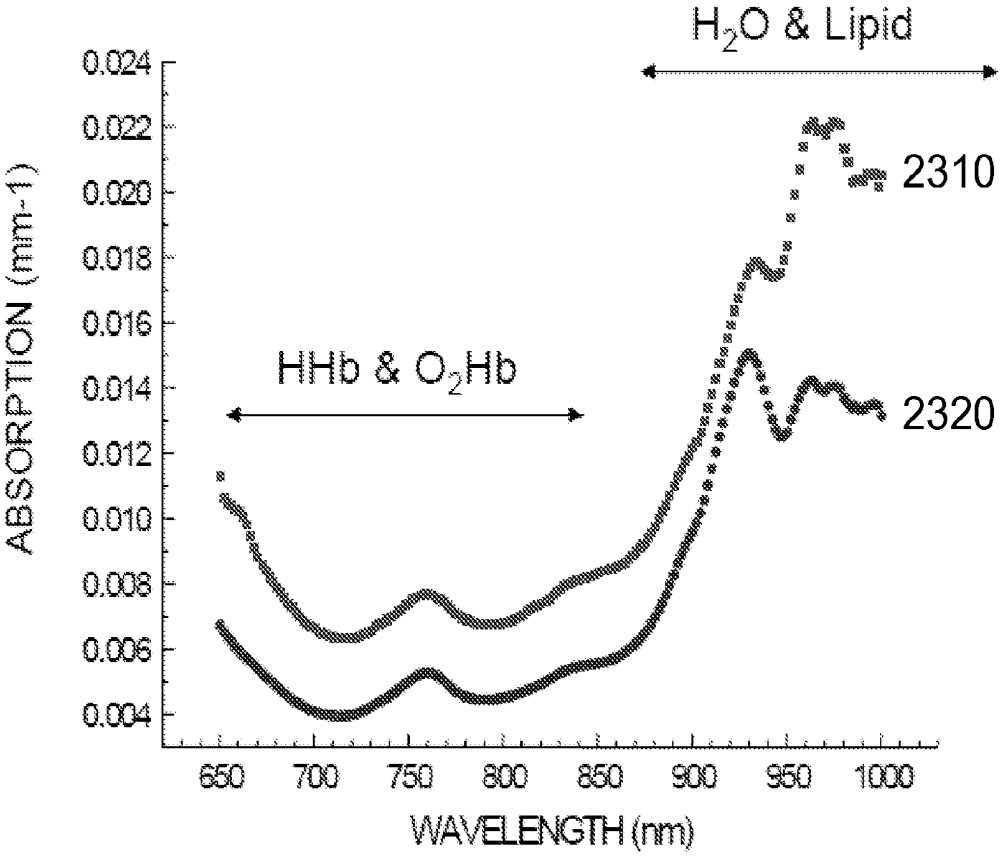

H2O & Lipid
HHb & O2Hb
2310
2320
ABSORPTION (mm-1)
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0.004
650
700
750
800
850
900
950
1000
WAVELENGTH (nm)

Fig. 23

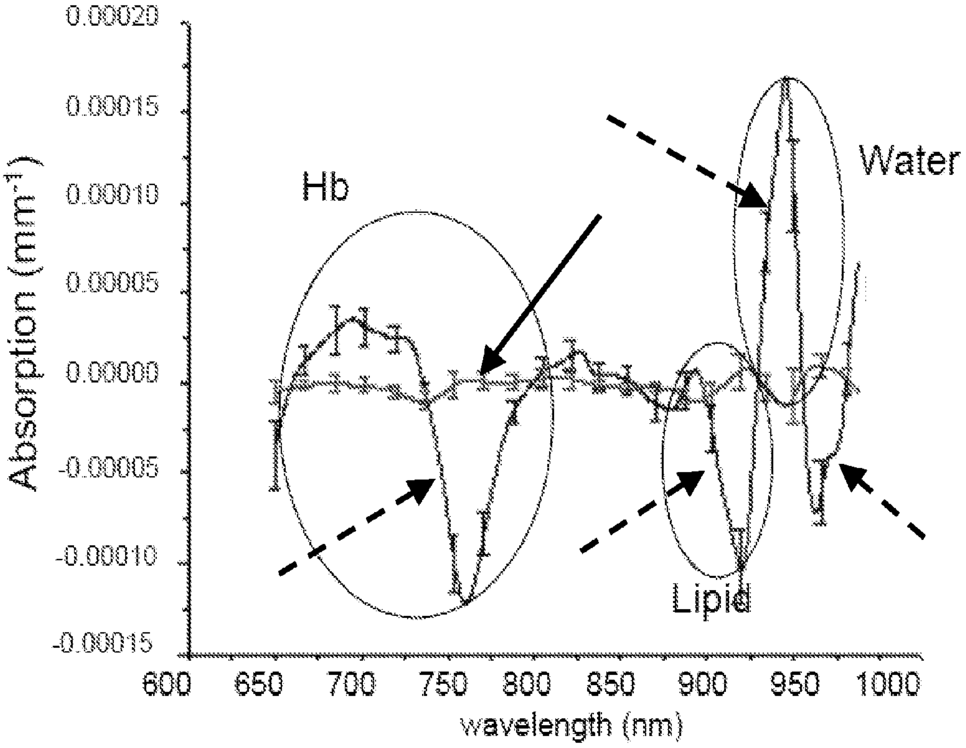

0.00020
0.00015
0.00010
0.00005
0.00000
-0.00005
-0.00010
-0.00015
Absorption (mm⁻¹)
600
650
700
750
800
850
900
950
1000
wavelength (nm)
Hb
Water
Lipid

Fig. 24

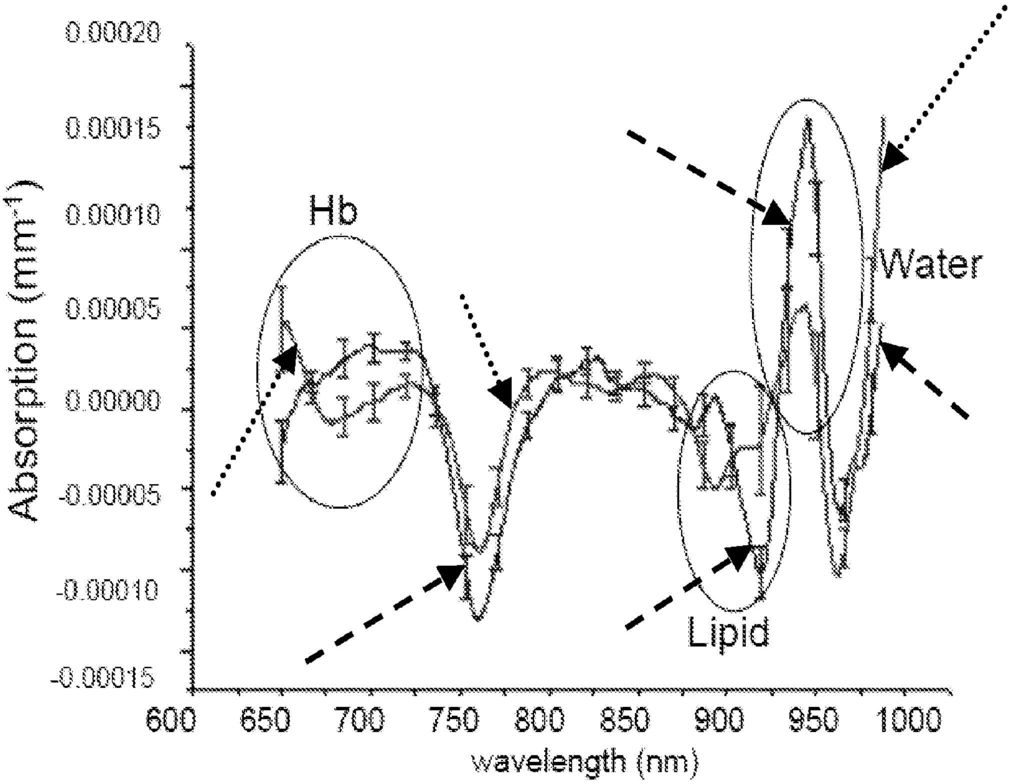

0.00020
0.00015
0.00010
0.00005
0.00000
-0.00005
-0.00010
-0.00015
Absorption (mm^{-1})
600
650
700
750
800
850
900
950
1000
wavelength (nm)
Hb
Water
Lipid

Fig. 25

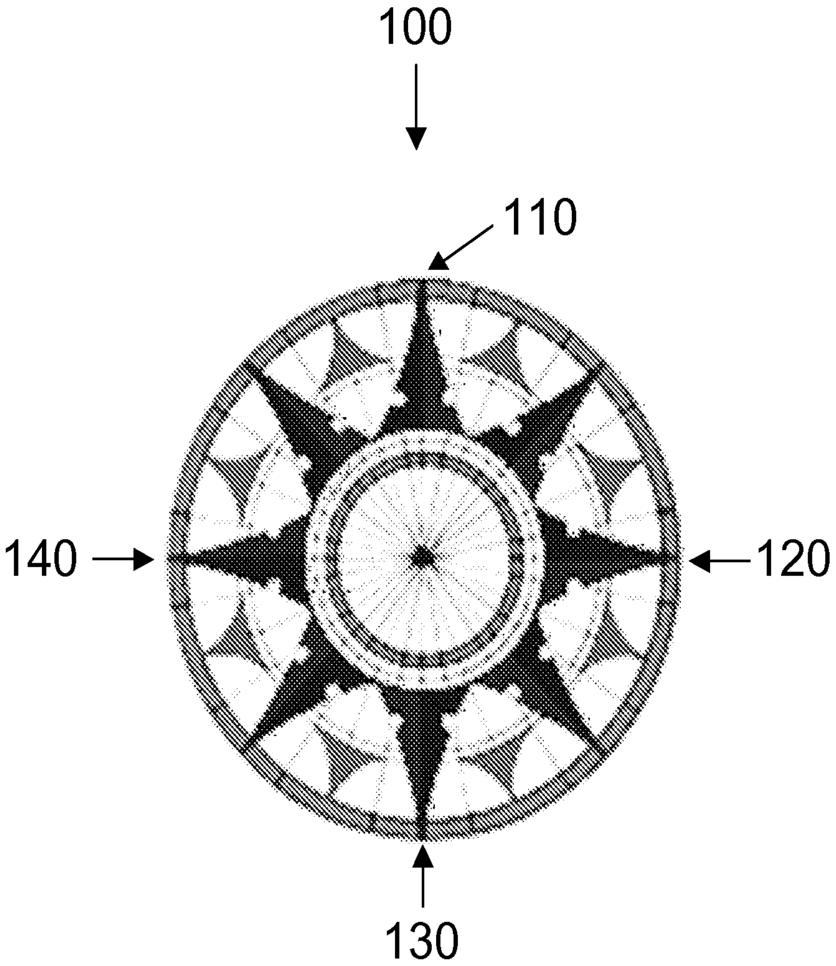


Fig. 26

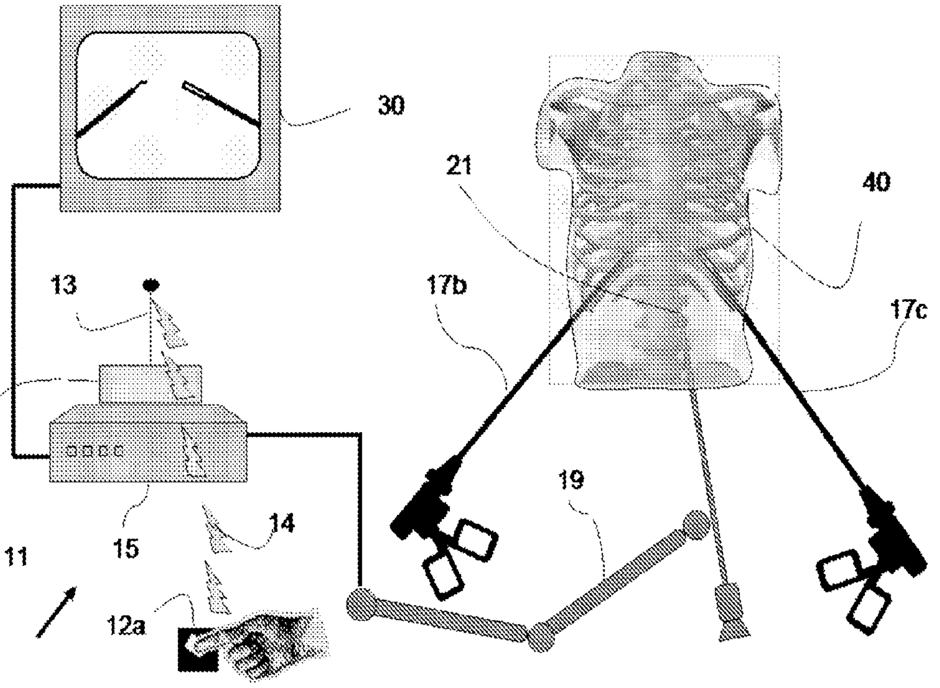


Fig. 27

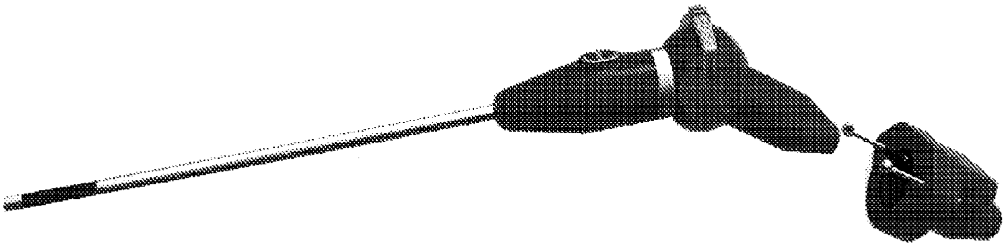


Fig. 28a

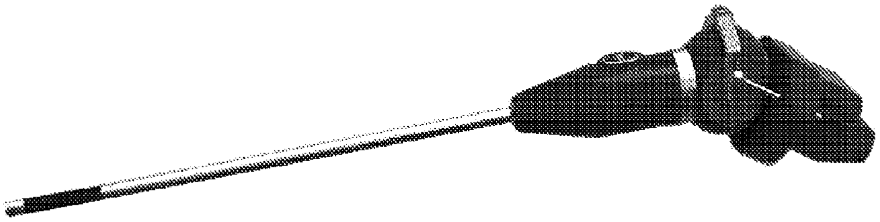


Fig. 28b

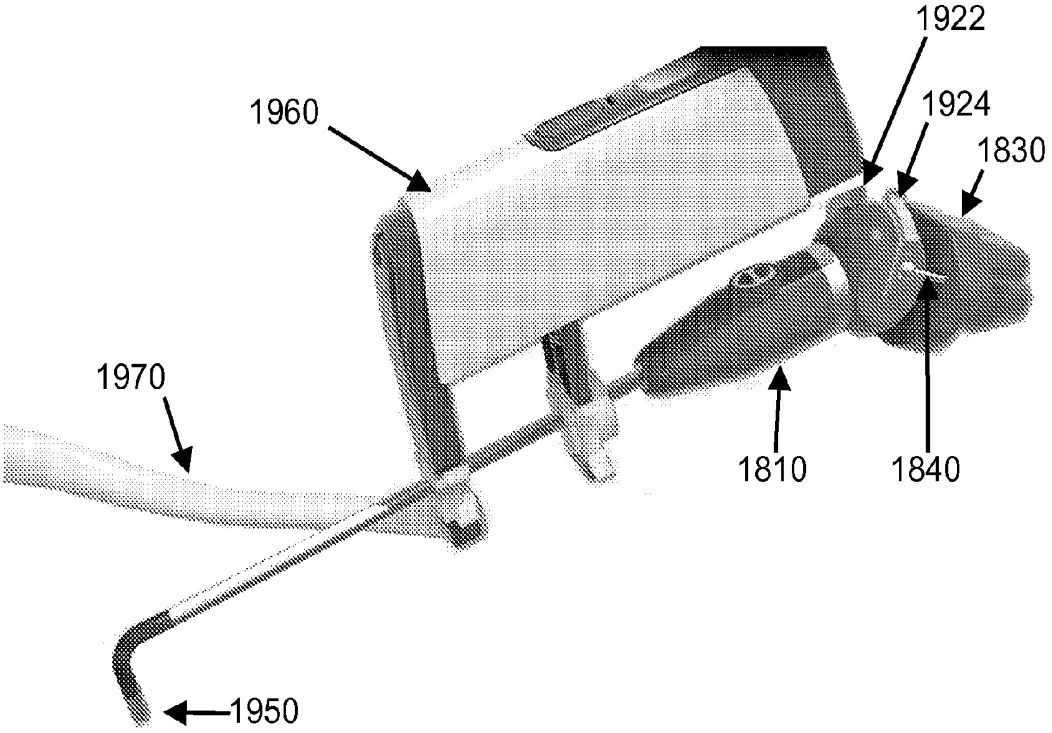


Fig. 29

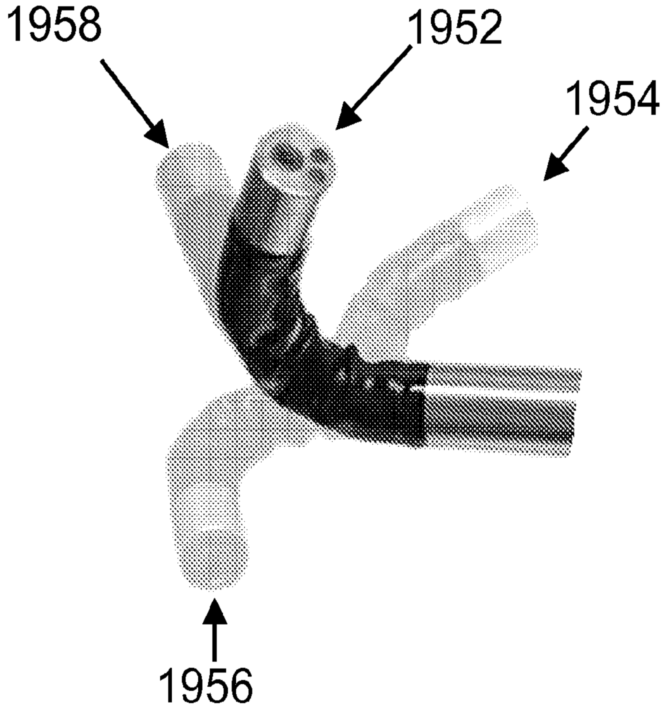


Fig. 30a

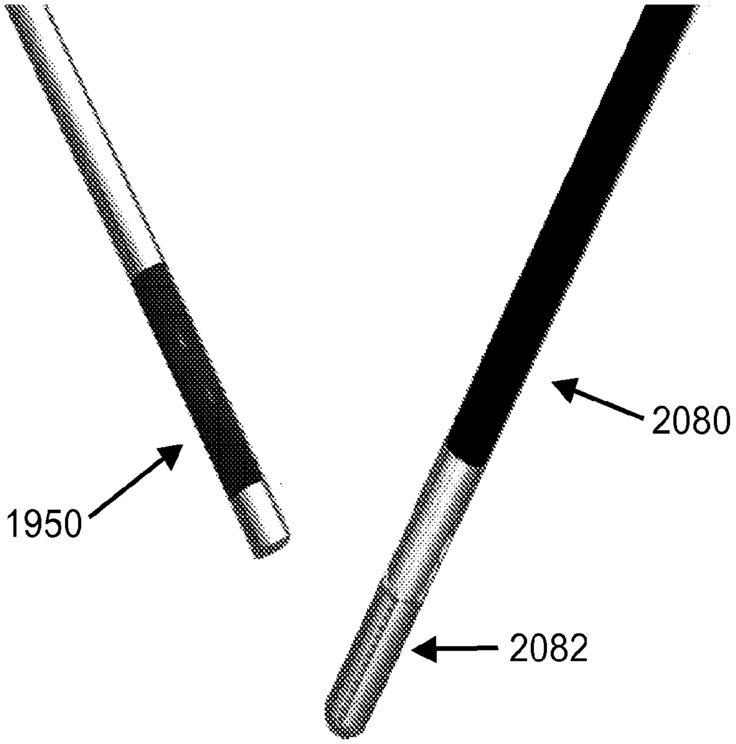


Fig. 30b

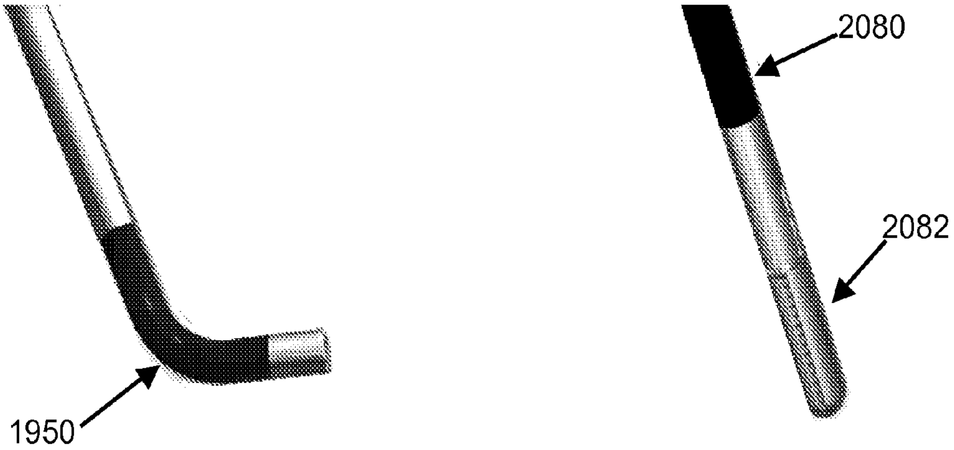


Fig. 30c

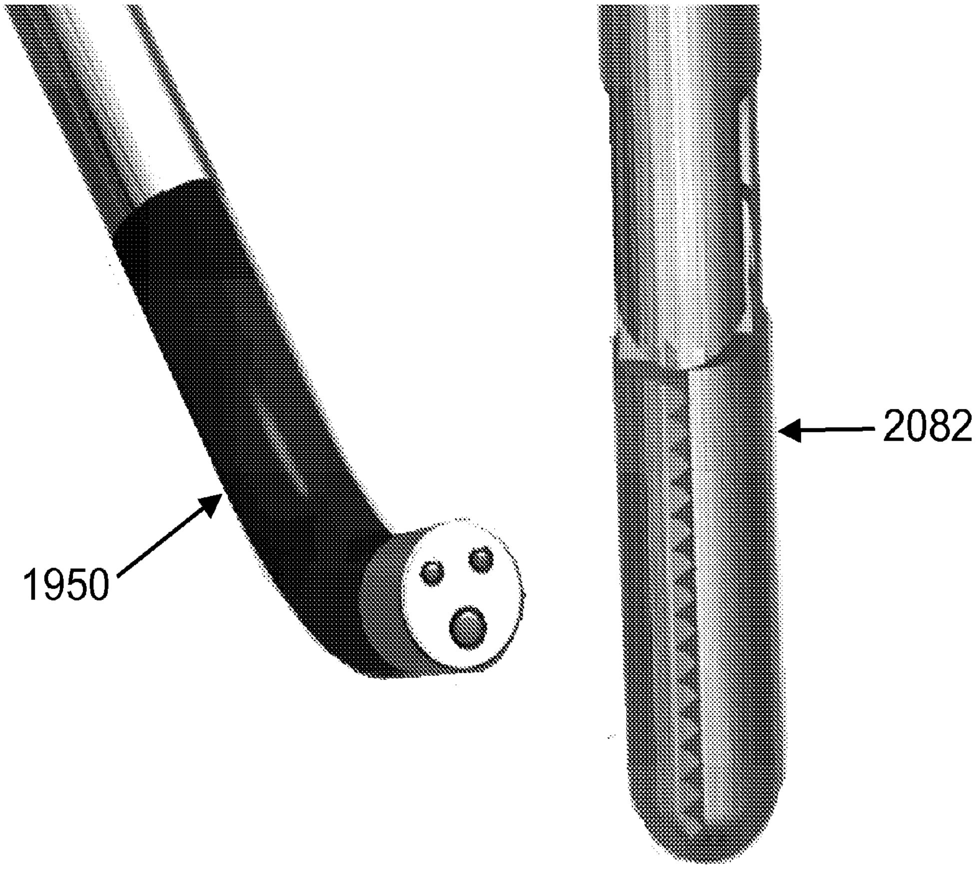


Fig. 30d

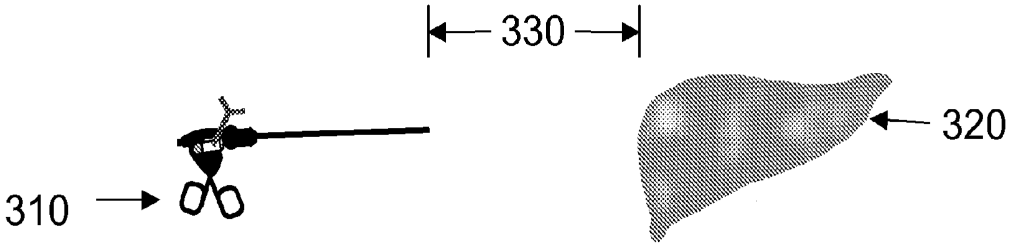


Fig. 31a

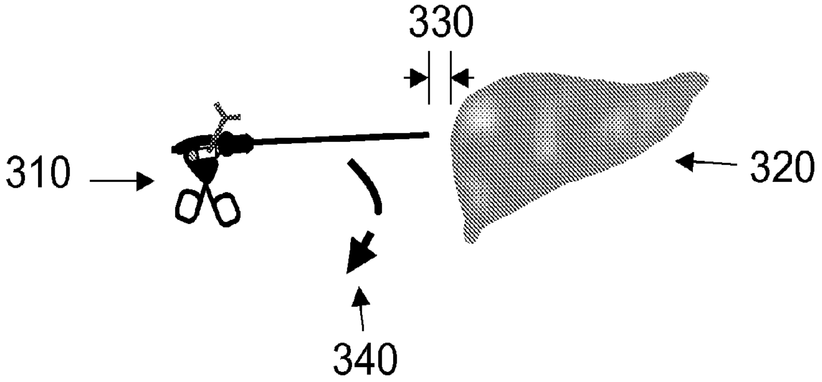


Fig. 31b

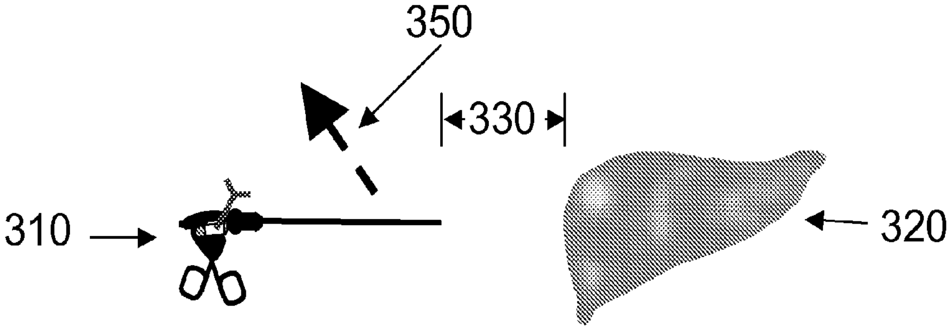


Fig. 31c

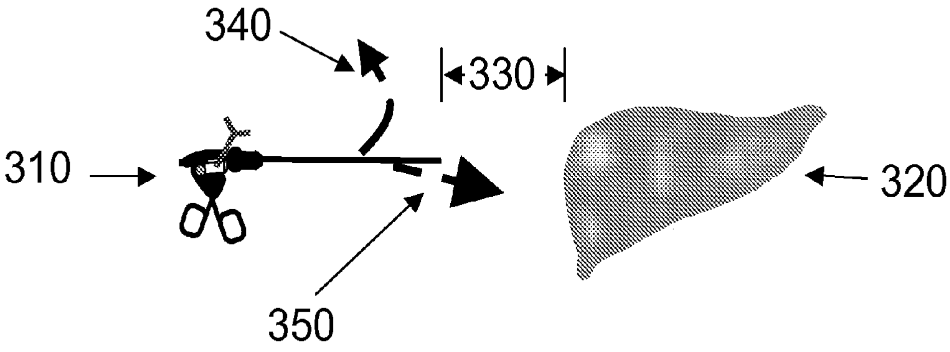


Fig. 31d

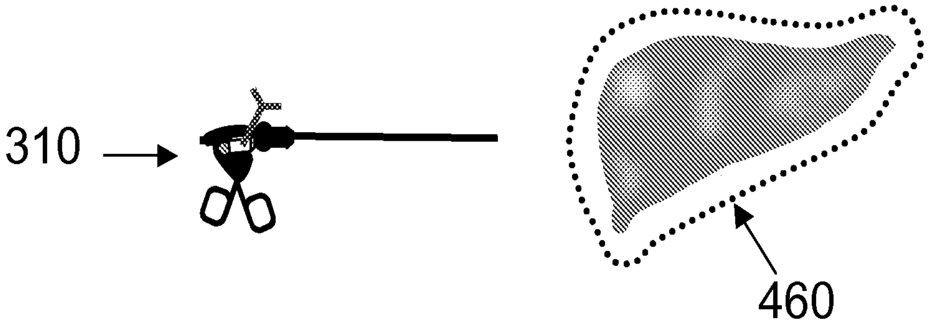


Fig. 32a

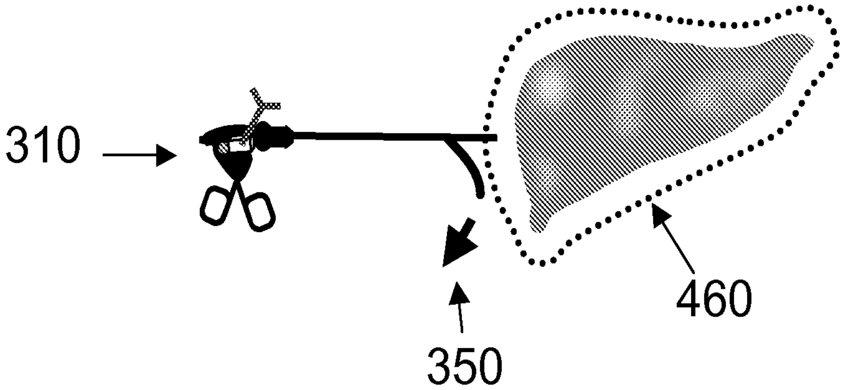


Fig. 32b

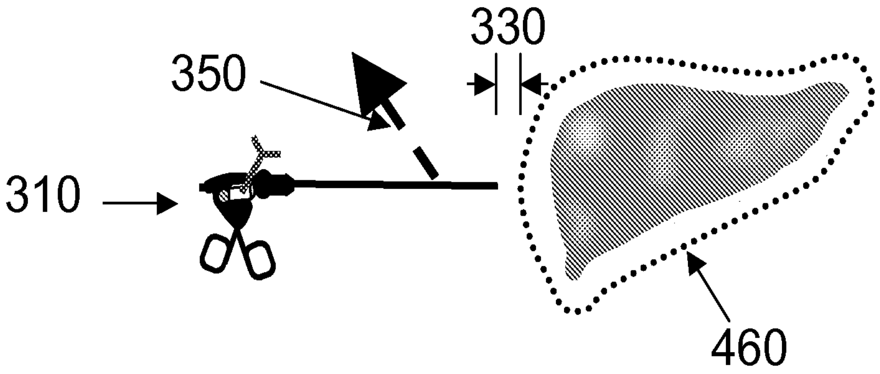


Fig. 32c

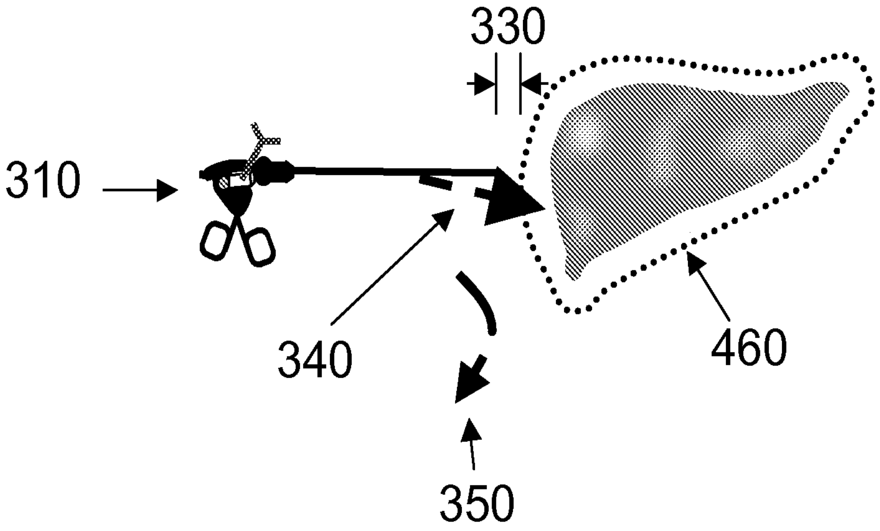


Fig. 32d

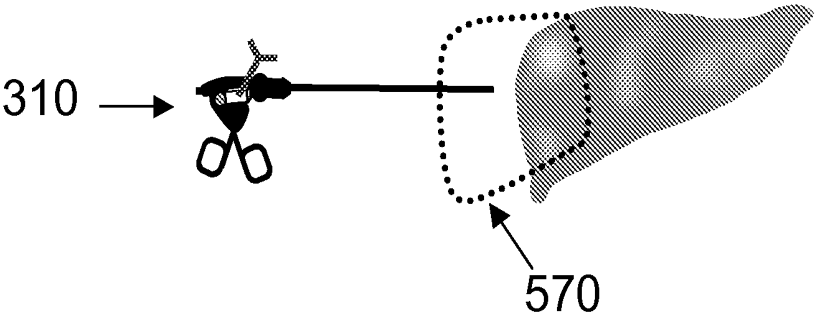


Fig. 33a

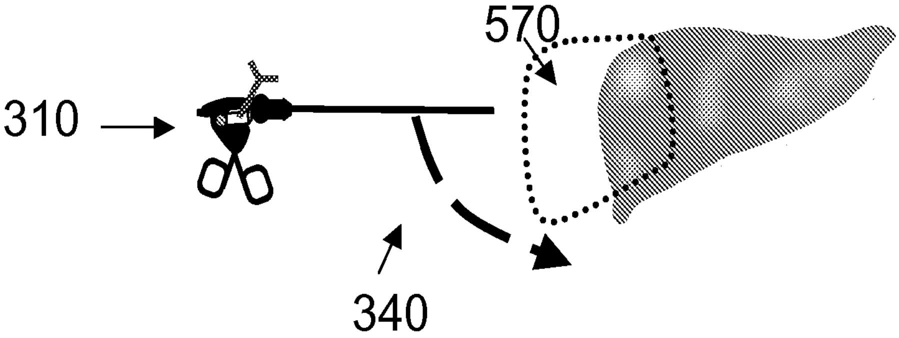


Fig. 33b

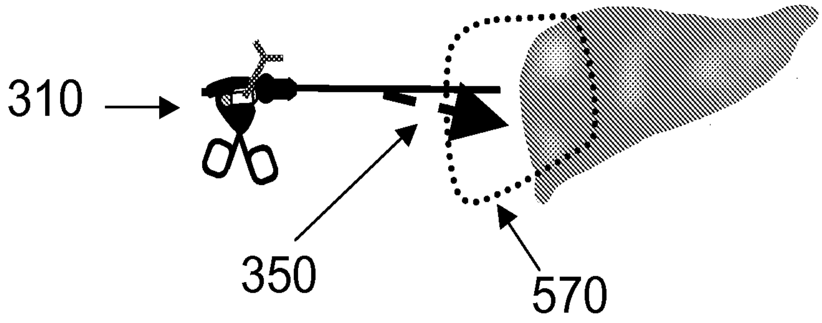


Fig. 33c

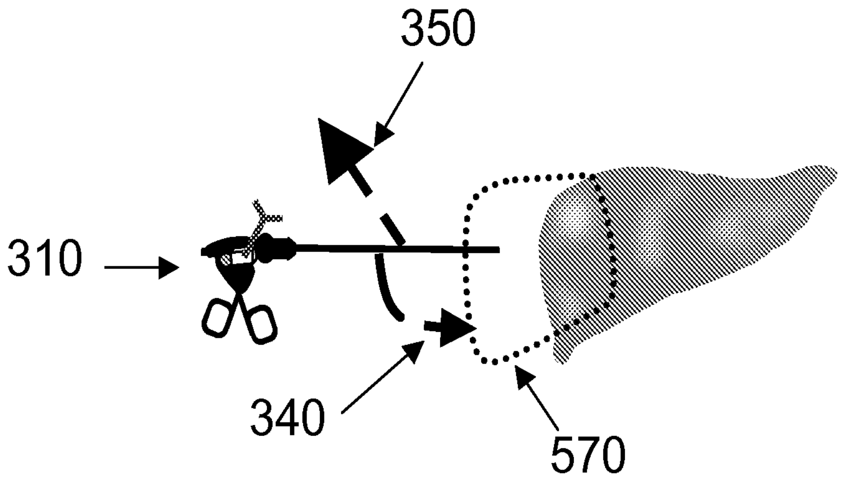


Fig. 33d

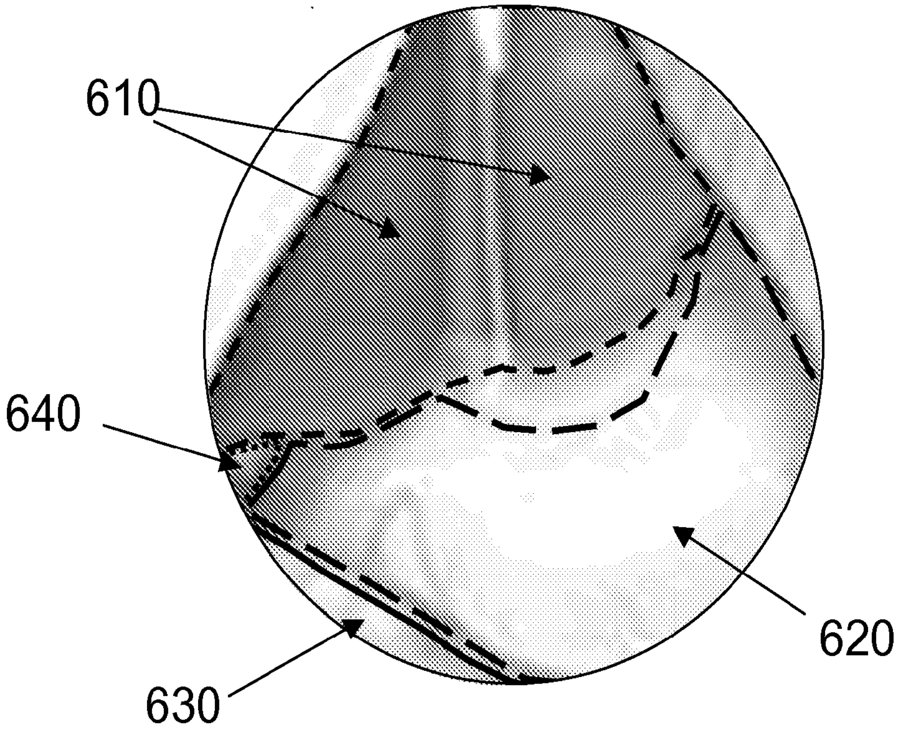


Fig. 34

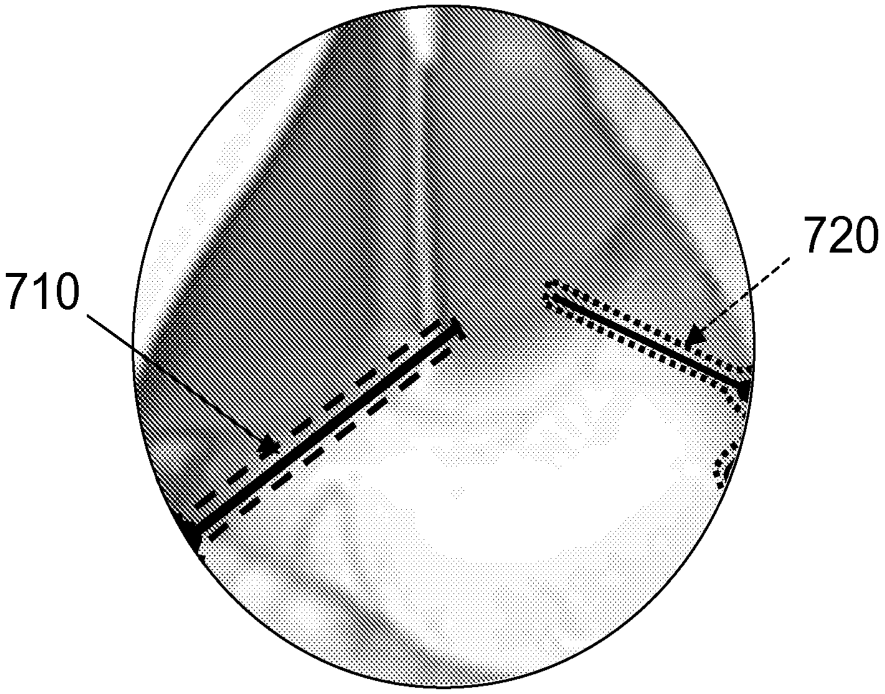


Fig. 35

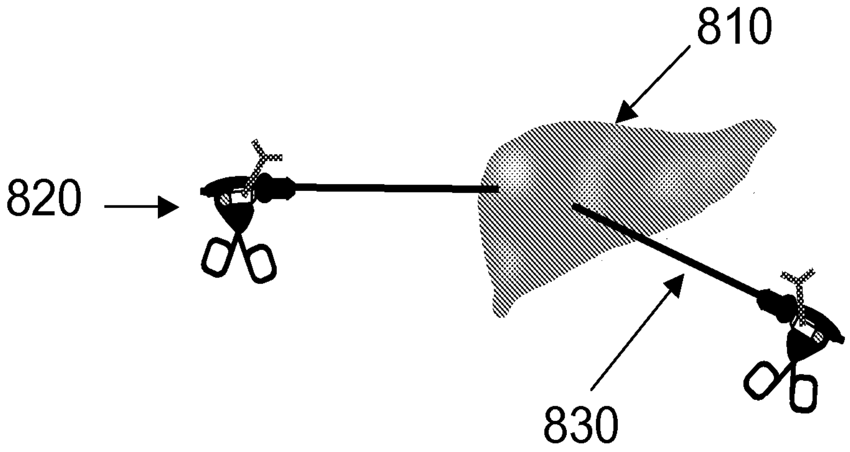


Fig. 36a

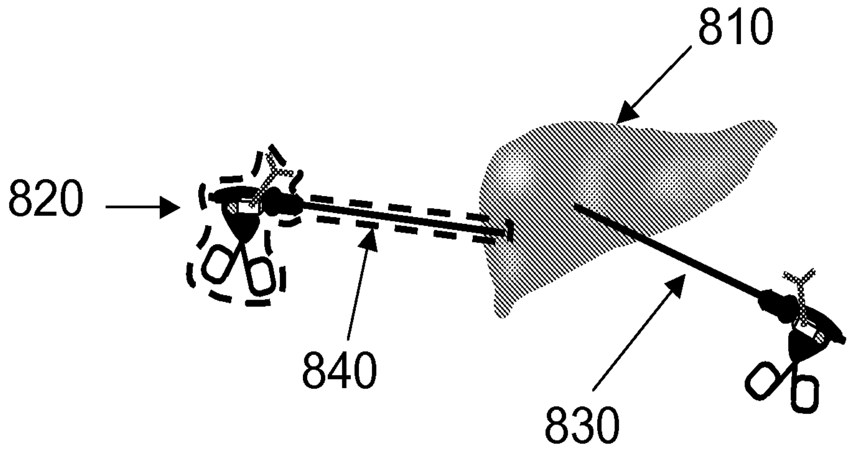


Fig. 36b

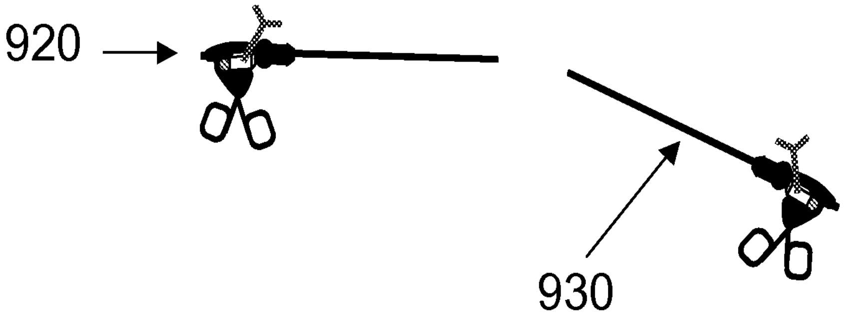


Fig. 37a

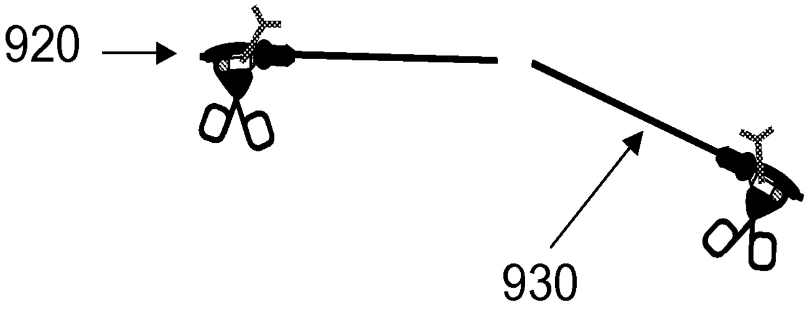


Fig. 37b

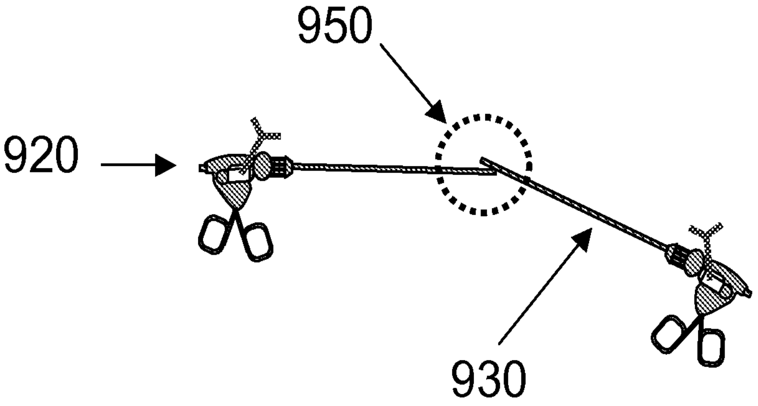


Fig. 37c

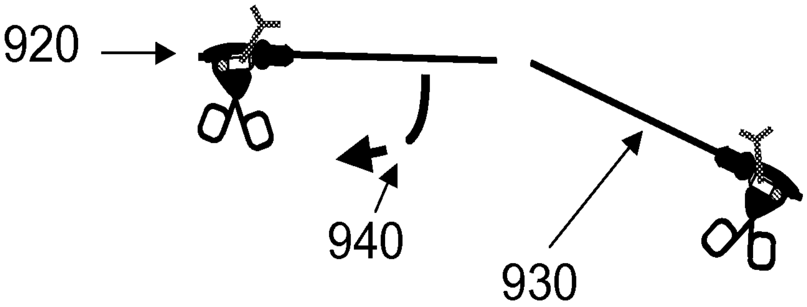


Fig. 37d

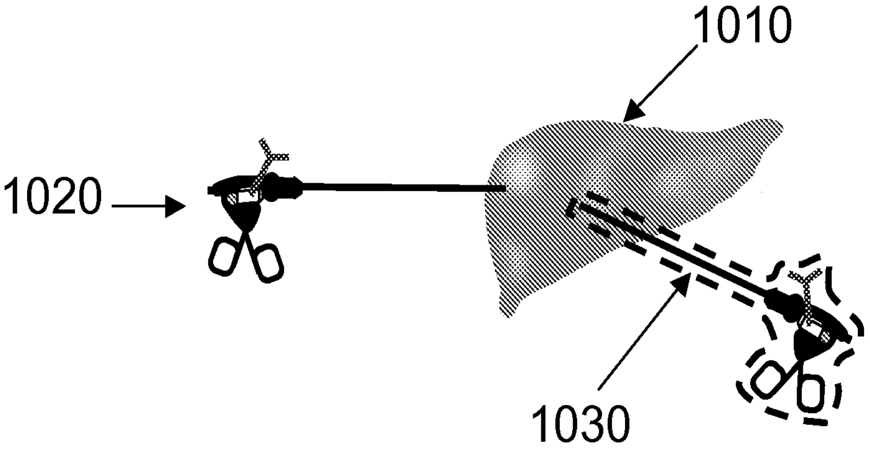


Fig. 38

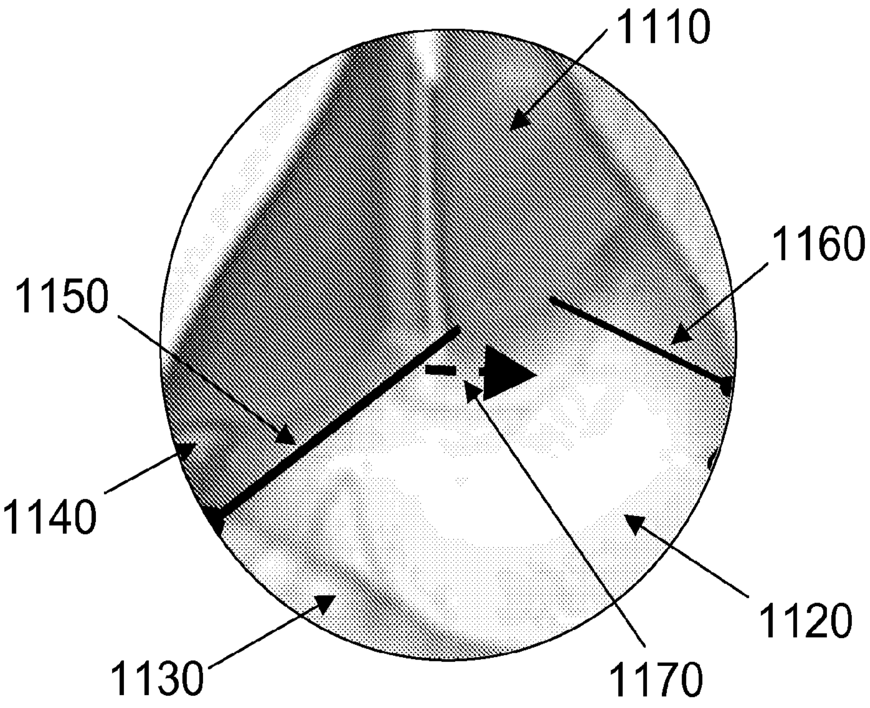


Fig. 39a

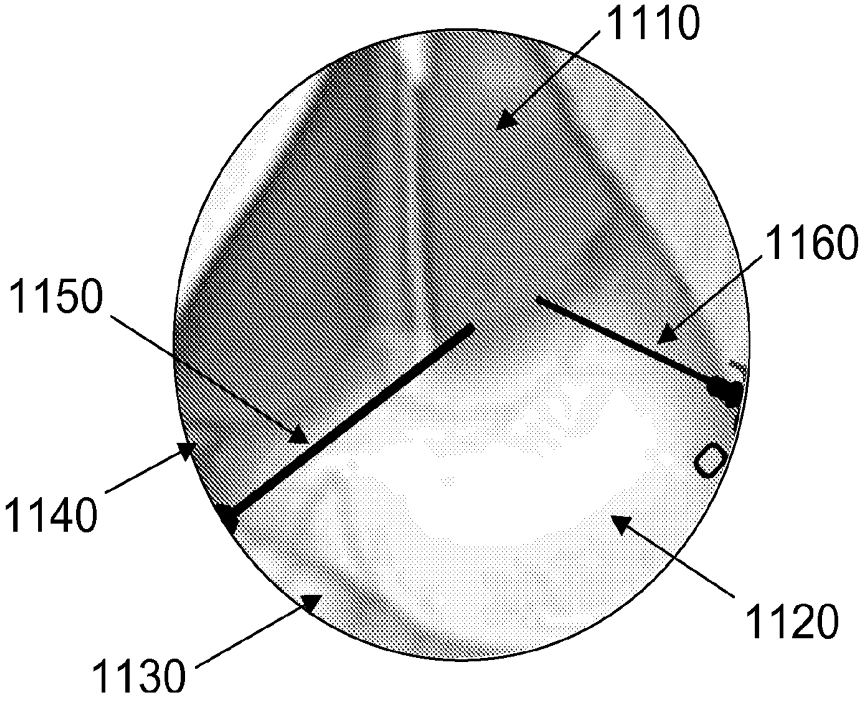


Fig. 39b

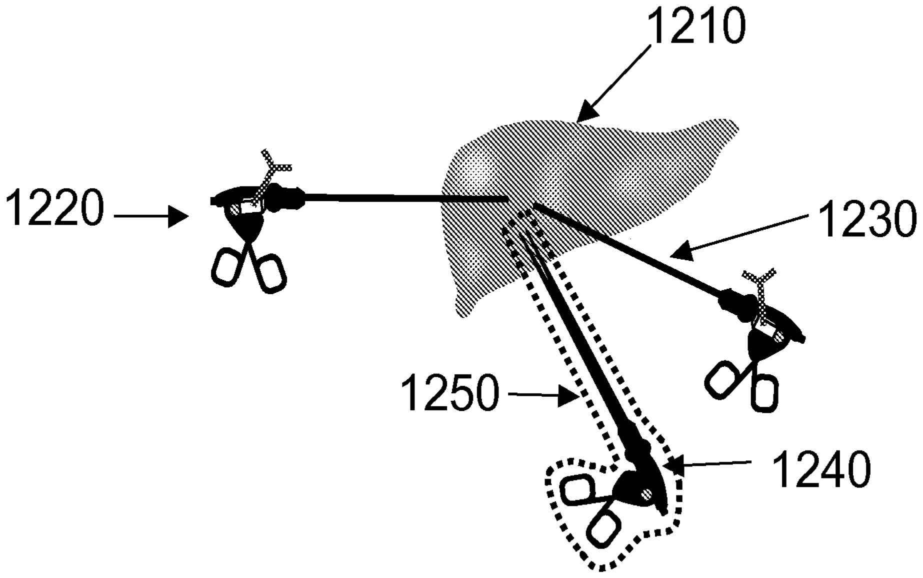


Fig. 40

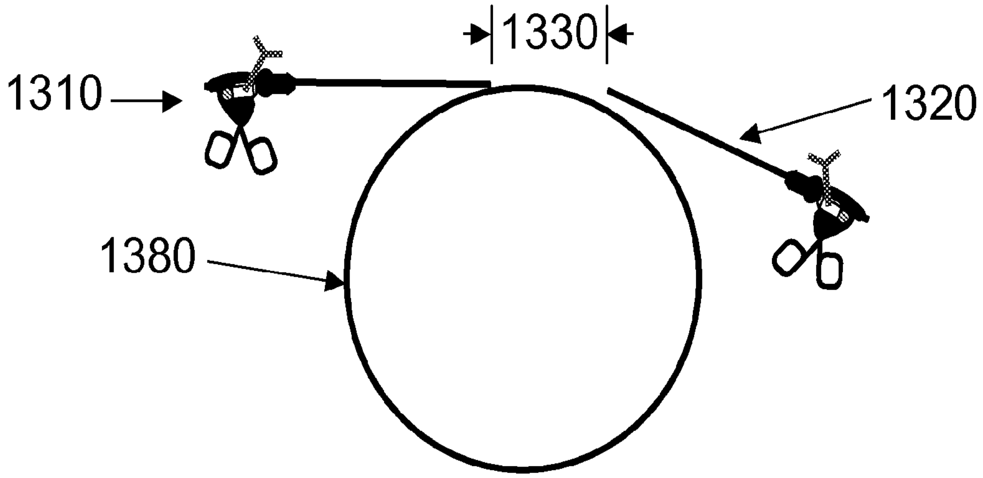


Fig. 41a

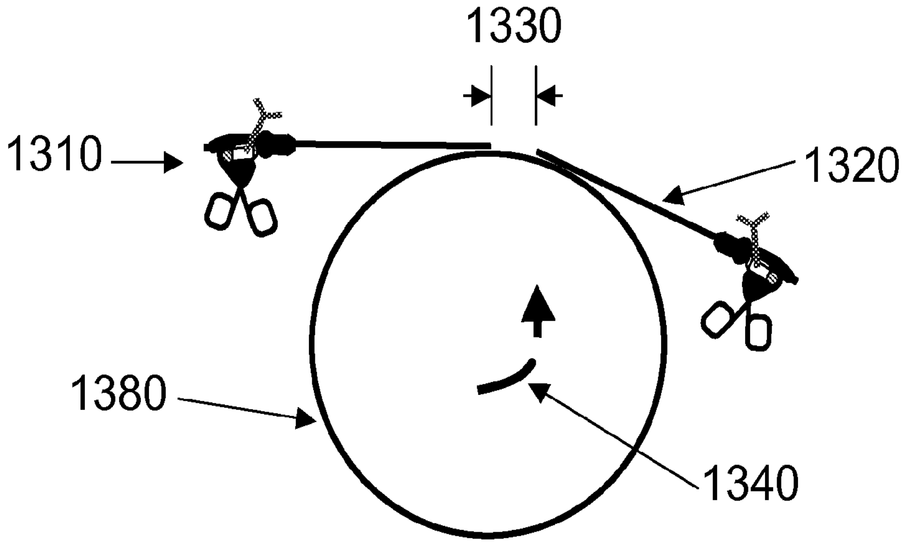


Fig. 41b

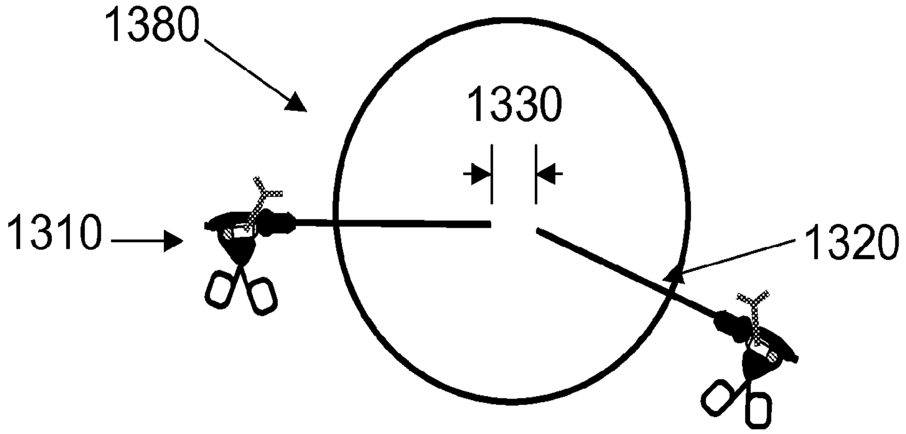


Fig. 41c

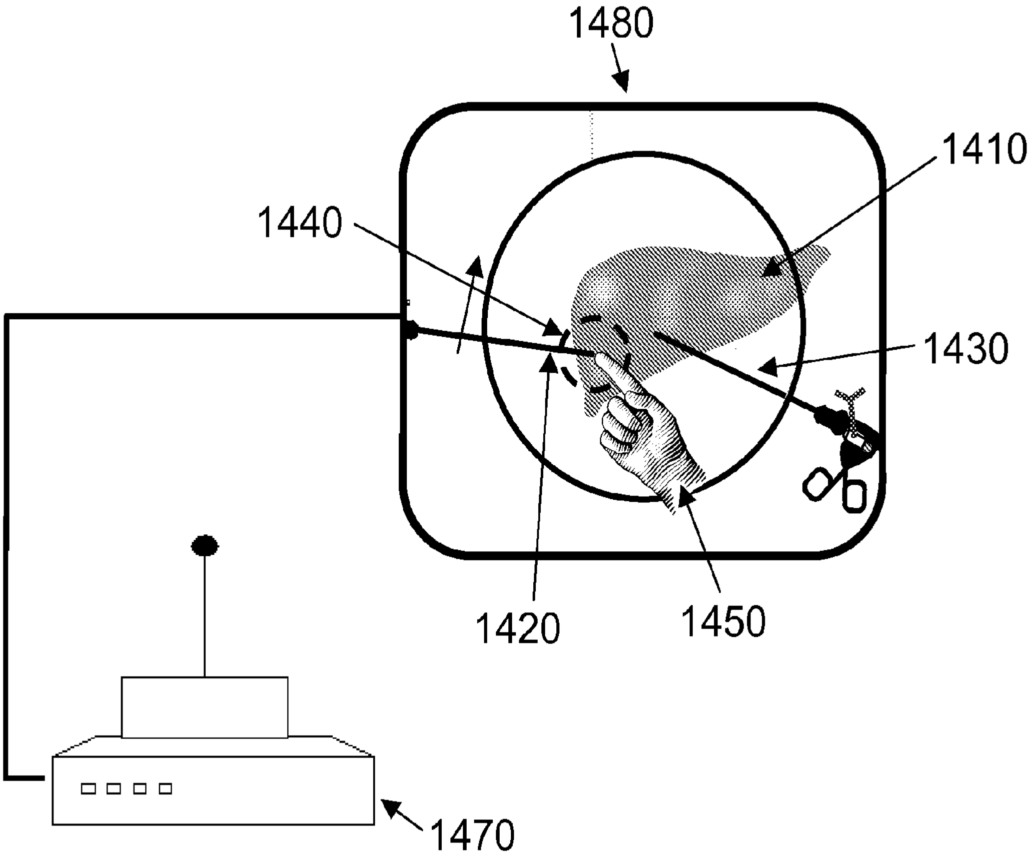


Fig. 42a

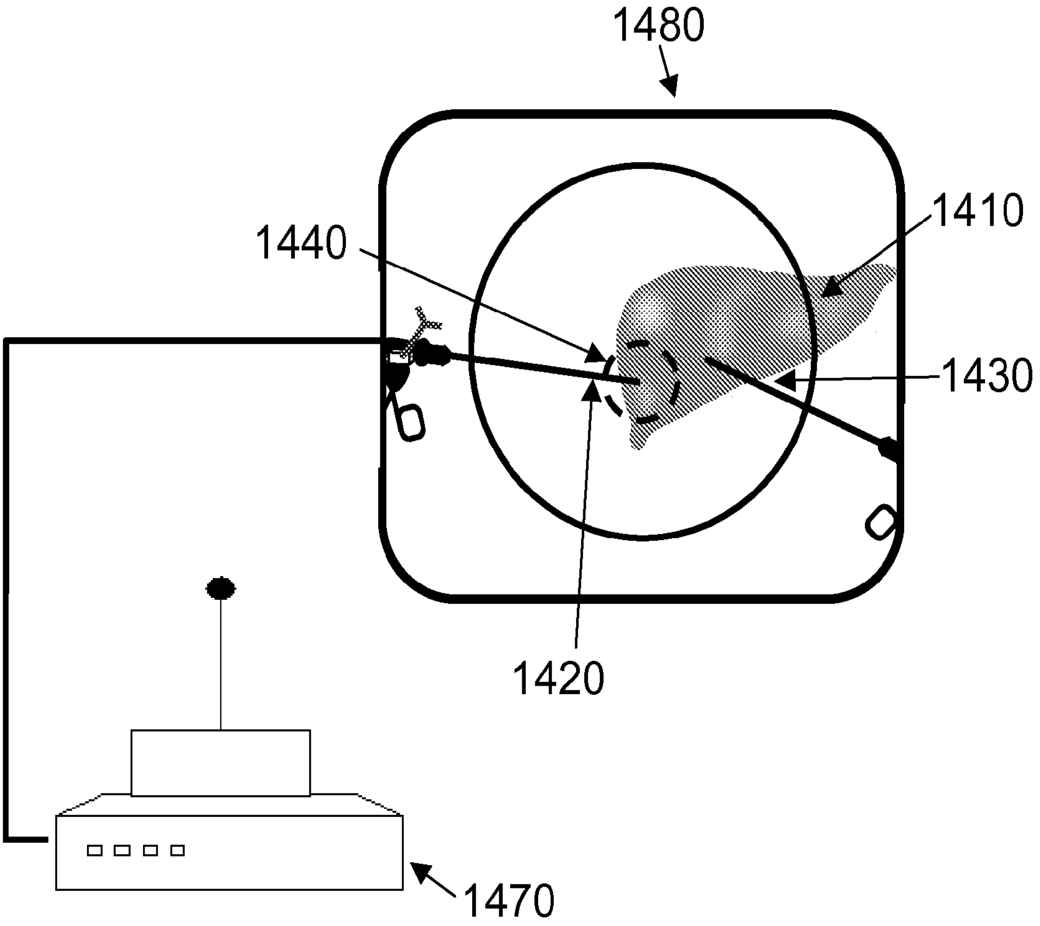


Fig. 42b

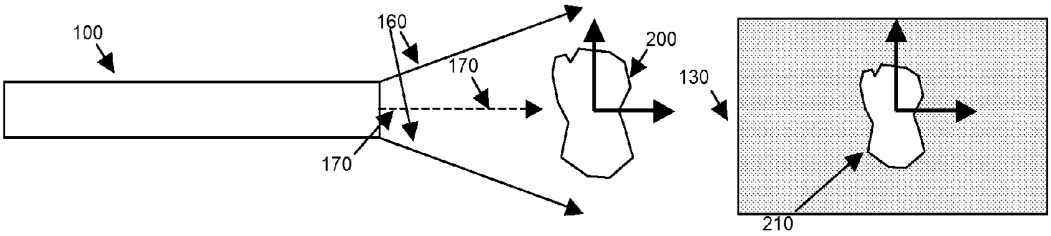


Fig. 43a

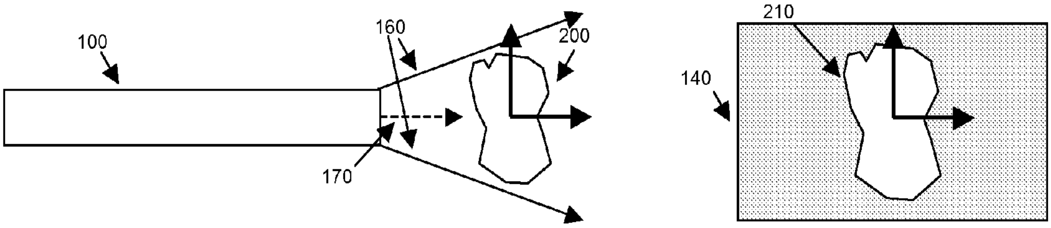


Fig. 43b

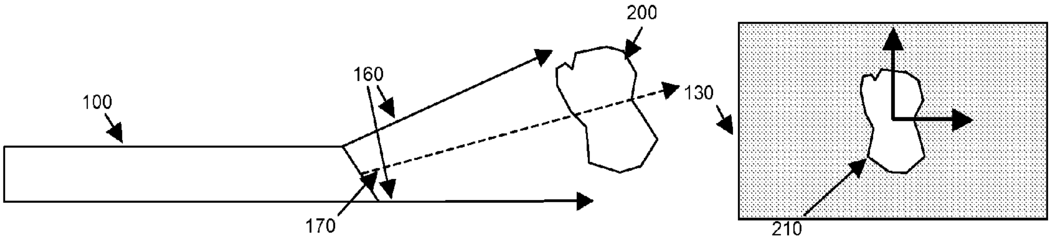


Fig. 43c

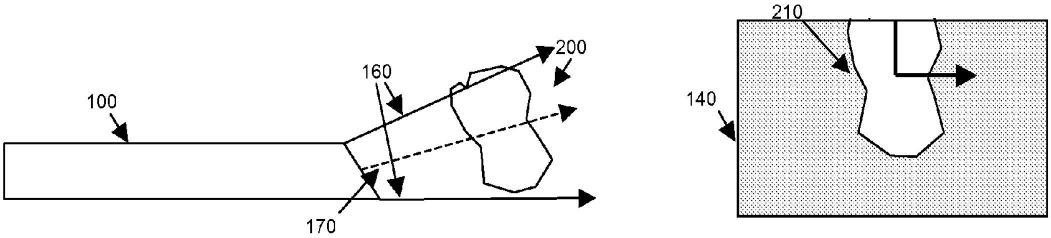


Fig. 43d

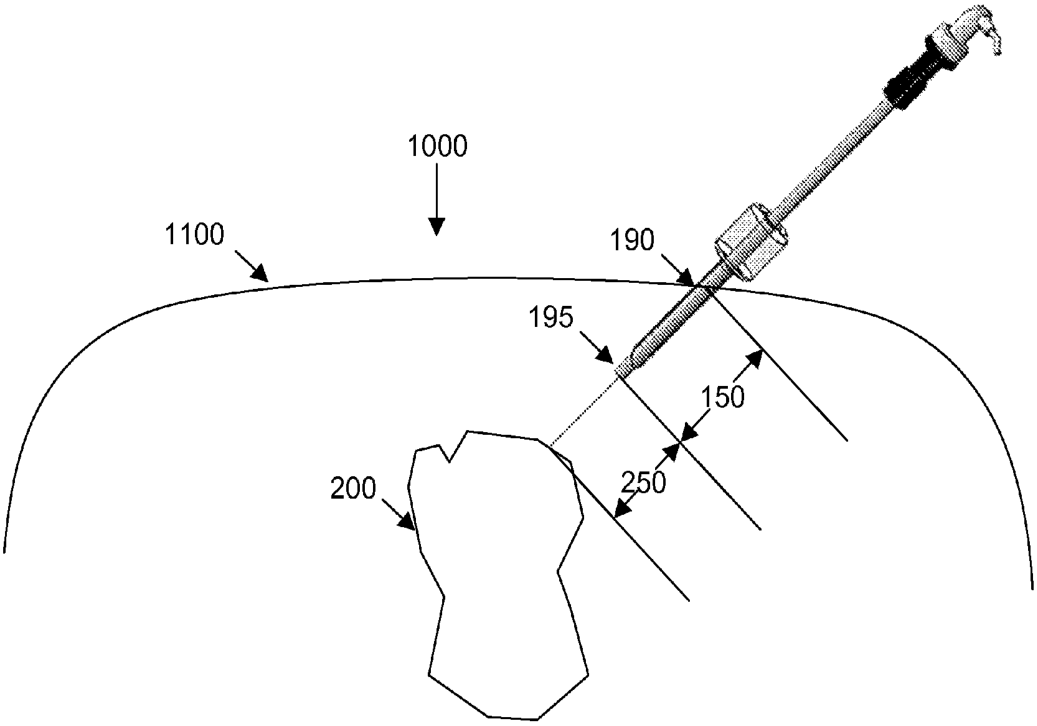


Fig. 44

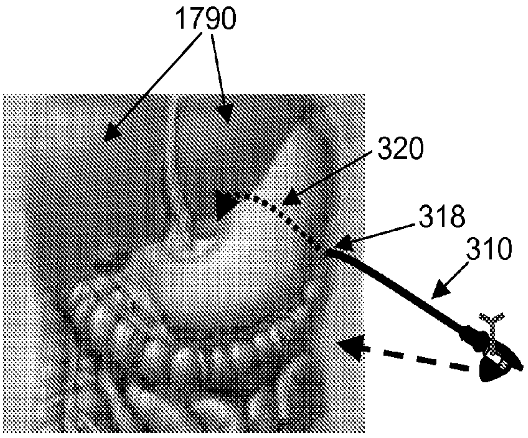


FIG. 45A

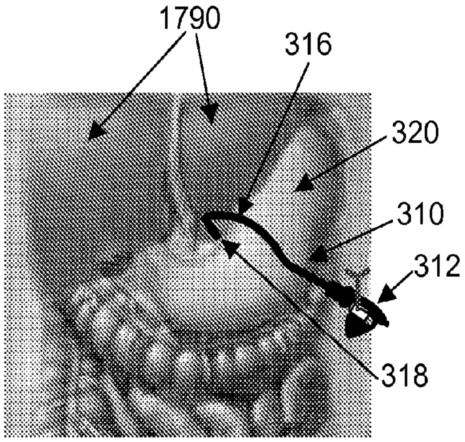


FIG. 45B

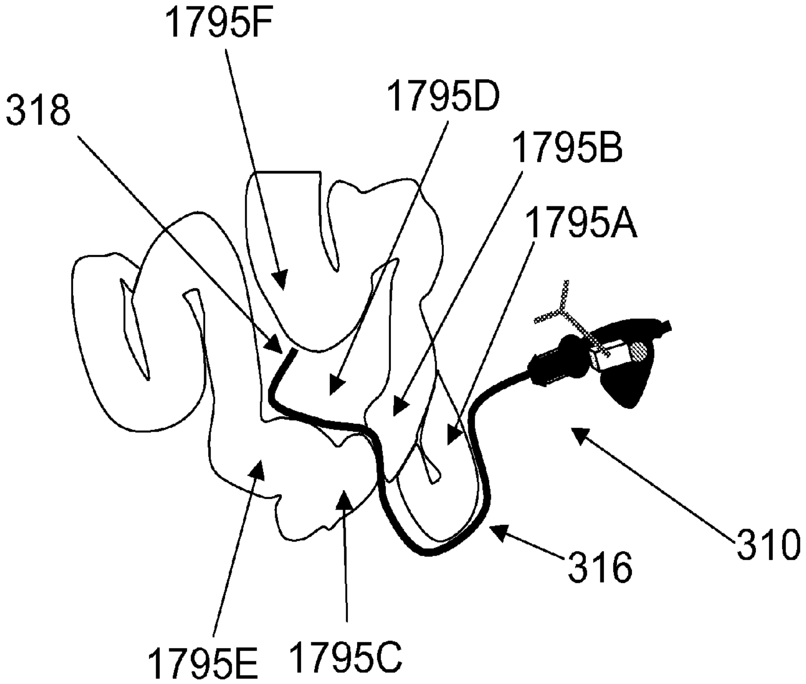


Fig. 46

DEVICE AND METHOD FOR ASSISTING LAPAROSCOPIC SURGERY - DIRECTING AND MANEUVERING ARTICULATING TOOL

FIELD OF THE INVENTION

[0001] The present invention generally pertains to a system and method for directing and maneuvering an articulating tool such as an endoscope during laparoscopic surgery.

BACKGROUND OF THE INVENTION

[0002] In laparoscopic surgery, the surgeon performs the operation through small holes using long instruments and observing the internal anatomy with an endoscope camera.

[0003] Laparoscopic surgery is becoming increasingly popular with patients because the scars are smaller and their period of recovery is shorter. Laparoscopic surgery requires special training for the surgeon and the theatre nursing staff. The equipment is often expensive and is not available in all hospitals.

[0004] During laparoscopic surgery, it is often required to shift the spatial placement of the endoscope in order to present the surgeon with an optimal view. Conventional laparoscopic surgery makes use of either human assistants that manually shift the instrumentation or, alternatively, robotic automated assistants. Automated assistants utilize interfaces that enable the surgeon to direct the mechanical movement of the assistant, achieving a shift in the camera view.

[0005] Research has suggested that these systems divert the surgeon's focus from the major task at hand. Therefore, technologies assisted by magnets and image processing have been developed to simplify interfacing control. In all such systems, the endoscope must be maneuvered such that it does not come into contact with other objects in the surgical field, such as other tools or the patient's organs, which can significantly complicate the maneuvering of the endoscope.

[0006] In addition, conventional laparoscopes provide the surgeon with a 2D image of the field of view, or use two cameras to provide a 3D image.

[0007] Therefore, there is need for a system in which the system comprises an endoscope or other surgical tool that can change shape, size or angulation so as to simplify maneuvering of the system and which comprises only a single camera.

[0008] Hence, there is still a long felt need for a method of directing a laparoscopic system to a desired location that includes control of the size, shape or angulation of at least one surgical tool and which uses a single camera to provide a 3D image.

SUMMARY OF THE INVENTION

[0009] It is an object of the present invention to disclose a system and method for directing and maneuvering an articulating tool such as an endoscope during laparoscopic surgery which uses a single camera to provide a 3D image.

[0010] It is another object of the present invention to disclose the surgical controlling system, additionally comprising at least one endoscope adapted to provide a real time image of said surgical environment.

[0011] It is another object of the present invention to disclose the surgical controlling system, wherein said tool is an endoscope.

[0012] It is another object of the present invention to disclose the surgical controlling system, wherein said tool comprises at least one proximity sensor positioned on the outer circumference of the same.

[0013] It is another object of the present invention to disclose the surgical controlling system, wherein said instructions comprise a predetermined set of rules selected from a group consisting of: most used tool rule, right tool rule, left tool rule, field of view rule, no fly zone rule, a route rule, environmental rule, operator input rule, proximity rule; collision prevention rule, history-based rule, tool-dependent ALLOWED and RESTRICTED movements rule, preferred volume zone rule, preferred tool rule, movement detection rule, tagged tool rule, change of speed rule and any combination thereof.

[0014] It is another object of the present invention to disclose the surgical controlling system, wherein said route rule comprises a communicable database storing predefined route in which said at least one surgical tool is adapted to move within said surgical environment; said predefined route comprises n 3D spatial positions of said at least one surgical tool; n is an integer greater than or equal to 2; said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said n 3D spatial positions of said predefined route, and said RESTRICTED movements are movements in which said location of said at least one surgical tool is substantially different from said n 3D spatial positions of said predefined route.

[0015] It is another object of the present invention to disclose the surgical controlling system, wherein said environmental rule comprises a comprises a communicable database; said communicable database adapted to receive at least one real-time image of said surgical environment and is adapted to perform real-time image processing of the same and to determine the 3D spatial position of hazards or obstacles in said surgical environment; said environmental rule is adapted to determine said ALLOWED and RESTRICTED movements according to said hazards or obstacles in said surgical environment, such that said RESTRICTED movements are movements in which said at least one surgical tool is located substantially in at least one of said 3D spatial positions, and said ALLOWED movements are movements in which the location of said at least one surgical tool is substantially different from said 3D spatial positions.

[0016] It is another object of the present invention to disclose the surgical controlling system, wherein said hazards or obstacles in said surgical environment are selected from a group consisting of tissue, a surgical tool, an organ, an endoscope and any combination thereof.

[0017] It is another object of the present invention to disclose the surgical controlling system, wherein said operator input rule comprises a communicable database; said communicable database is adapted to receive an input from the operator of said system regarding said ALLOWED and RESTRICTED movements of said at least one surgical tool.

[0018] It is another object of the present invention to disclose the surgical controlling system, wherein said input comprises n 3D spatial positions; n is an integer greater than or equal to 2; wherein at least one of which is defined as ALLOWED location and at least one of which is defined as RESTRICTED location, such that said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said at least one surgical tool is substantially different from said n 3D spatial positions.

[0019] It is another object of the present invention to disclose the surgical controlling system, wherein said input comprises at least one rule according to which ALLOWED and RESTRICTED movements of said at least one surgical tool are determined, such that the spatial position of said at least one surgical tool is controlled by said controller according to said ALLOWED and RESTRICTED movements.

[0020] It is another object of the present invention to disclose the surgical controlling system, wherein said predetermined set of rules comprises a member of a group consisting of: most used tool, right tool rule, left tool rule, field of view rule, no fly zone rule, route rule, environmental rule, operator input rule, proximity rule, collision prevention rule, preferred volume zone rule, preferred tool rule, movement detection rule, history-based rule, tool-dependent ALLOWED and RESTRICTED movements rule, and any combination thereof.

[0021] It is another object of the present invention to disclose the surgical controlling system, wherein said operator input rule converts an ALLOWED movement to a RESTRICTED movement and a RESTRICTED movement to an ALLOWED movement.

[0022] It is another object of the present invention to disclose the surgical controlling system, wherein said proximity rule is adapted to define a predetermined distance between at least two surgical tools; said ALLOWED movements are movements which are within the range or out of the range of said predetermined distance, and said RESTRICTED movements are movements which are out of the range or within the range of said predetermined distance.

[0023] It is another object of the present invention to disclose the surgical controlling system, wherein said proximity rule is adapted to define a predetermined angle between at least three surgical tools; said ALLOWED movements are movements which are within the range or out of the range of said predetermined angle, and said RESTRICTED movements are movements which are out of the range or within the range of said predetermined angle.

[0024] It is another object of the present invention to disclose the surgical controlling system, wherein said collision prevention rule is adapted to define a predetermined distance between said at least one surgical tool and an anatomical element within said surgical environment; said ALLOWED movements are movements which are in a range that is larger than said predetermined distance, and said RESTRICTED movements are movements which is in a range that is smaller than said predetermined distance.

[0025] It is another object of the present invention to disclose the surgical controlling system, wherein said anatomical element is selected from a group consisting of tissue, organ, another surgical tool and any combination thereof.

[0026] It is another object of the present invention to disclose the surgical controlling system, wherein at least one of the following is being held true (a) said system additionally comprises an endoscope; said endoscope is adapted to provide real-time image of said surgical environment; (b) at least one of said surgical tools is an endoscope adapted to provide at least one real-time image of said surgical environment.

[0027] It is another object of the present invention to disclose the surgical controlling system, wherein said right tool rule is adapted to determine said ALLOWED movement of said endoscope according to the movement of the surgical tool positioned to right of said endoscope; further wherein said left tool rule is adapted to determine said ALLOWED movement of said endoscope according to the movement of the surgical tool positioned to left of said endoscope.

[0028] It is another object of the present invention to disclose the surgical controlling system, wherein said tagged tool rule comprises means adapted to tag at least one surgical tool within said surgical environment and to determine said ALLOWED movement of said endoscope to constantly track the movement of said tagged surgical tool.

[0029] It is another object of the present invention to disclose the surgical controlling system, wherein said field of view rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the combination of all of said n 3D spatial positions provides a predetermined field of view; said field of view rule is adapted to determine said ALLOWED movement of said endoscope within said n 3D spatial positions so as to maintain a constant field of view, such that said ALLOWED movements are movements in which said endoscope is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said endoscope is substantially different from said n 3D spatial positions.

[0030] It is another object of the present invention to disclose the surgical controlling system, wherein said preferred volume zone rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; said n 3D spatial positions provides said preferred volume zone; said preferred volume zone rule is adapted to determine said ALLOWED movement of said endoscope within said n 3D spatial positions and RESTRICTED movement of said endoscope outside said n 3D spatial positions, such that said ALLOWED movements are movements in which said endoscope is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said endoscope is substantially different from said n 3D spatial positions.

[0031] It is another object of the present invention to disclose the surgical controlling system, wherein said preferred tool rule comprises a communicable database, said database stores a preferred tool; said preferred tool rule is adapted to determine said ALLOWED movement of said endoscope to constantly track the movement of said preferred tool.

[0032] It is another object of the present invention to disclose the surgical controlling system, wherein said no fly zone rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; said n 3D spatial positions define a predetermined volume within said surgical environment; said no fly zone rule is adapted to determine said RESTRICTED movement if said movement is within said no fly zone and ALLOWED movement if said movement is outside said no fly zone, such that said RESTRICTED movements are movements in which said at least one of said surgical tool is located substantially in at least one of said n 3D spatial positions, and said ALLOWED movements are movements in which the location of said at least one endoscope is substantially different from said n 3D spatial positions.

[0033] It is another object of the present invention to disclose the surgical controlling system, wherein said most used tool rule comprises a communicable database counting the amount of movement of each said surgical tool; said most used tool rule is adapted to constantly position said endoscope to track the movement of the most moved surgical tool.

[0034] It is another object of the present invention to disclose the surgical controlling system, wherein said system further comprises a maneuvering subsystem communicable with said controller, said maneuvering subsystem is adapted to spatially reposition said at least one surgical tool during a surgery according to said predetermined set of rules; further wherein said system is adapted to alert the physician of said RESTRICTED movement of said at least one surgical tool.

[0035] It is another object of the present invention to disclose the surgical controlling system, wherein said alert is selected from a group consisting of audio signaling, voice signaling, light signaling, flashing signaling and any combination thereof.

[0036] It is another object of the present invention to disclose the surgical controlling system, wherein said ALLOWED movement is permitted by said controller and said RESTRICTED movement is denied by said controller.

[0037] It is another object of the present invention to disclose the surgical controlling system, wherein said history-based rule comprises a communicable database storing each 3D spatial position of each said surgical tool, such that each movement of each surgical tool is stored; said history-based rule is adapted to determine said ALLOWED and RESTRICTED movements according to historical movements of said at least one surgical tool, such that said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said 3D spatial positions, and said RESTRICTED movements are movements in which the location of said at least one surgical tool is substantially different from said n 3D spatial positions.

[0038] It is another object of the present invention to disclose the surgical controlling system, wherein said tool-dependent ALLOWED and RESTRICTED movements rule comprises a communicable database; said communicable database is adapted to store predetermined characteristics of at least one of said surgical tool; said tool-dependent ALLOWED and RESTRICTED movements rule is adapted to determine said ALLOWED and RESTRICTED movements according to said predetermined characteristics of said surgical tool; such that ALLOWED movements are movements of said endoscope which track said surgical tool having said predetermined characteristics.

[0039] It is another object of the present invention to disclose the surgical controlling system, wherein said predetermined characteristics of said surgical tool are selected from a group consisting of: physical dimensions, structure, weight, sharpness, and any combination thereof.

[0040] It is another object of the present invention to disclose the surgical controlling system, wherein said movement detection rule comprises a communicable database comprising the real-time 3D spatial positions of each said surgical tool; said movement detection rule is adapted to detect movement of said at least one surgical tool when a change in said 3D spatial positions is received, such that said ALLOWED movements are movements in which said endoscope is re-directed to focus on said moving surgical tool.

[0041] It is another object of the present invention to disclose the surgical controlling system, further comprising a maneuvering subsystem communicable with said controller, said maneuvering subsystem is adapted to spatially reposition said at least one surgical tool during a surgery according to said predetermined set of rules, such that if said movement of said at least one surgical tool is a RESTRICTED movement, said maneuvering subsystem prevents said movement.

[0042] It is another object of the present invention to disclose the surgical controlling system, wherein said at least one location estimating means comprises at least one endoscope adapted to acquire real-time images of said surgical environment within said human body; and at least one surgical instrument spatial location software adapted to receive said real-time images of said surgical environment and to estimate said 3D spatial position of said at least one surgical tool.

[0043] It is another object of the present invention to disclose the surgical controlling system, wherein said at least one location estimating means comprises (a) at least one element selected from a group consisting of optical imaging means, radio frequency transmitting and receiving means, at least one mark on said at least one surgical tool and any combination thereof; and, (b) at least one surgical instrument spatial location software adapted to estimate said 3D spatial position of said at least one surgical tool by means of said element.

[0044] It is another object of the present invention to disclose the surgical controlling system, wherein said at least one location estimating means is an interface subsystem between a surgeon and said at least one surgical tool, the interface subsystem comprising:

[0045] a. at least one array comprising N regular or pattern light sources, where N is a positive integer;

[0046] b. at least one array comprising M cameras, each of the M cameras, where M is a positive integer;

[0047] c. optional optical markers and means for attaching the optical marker to the at least one surgical tool; and;

[0048] d. a computerized algorithm operable via the controller, the computerized algorithm adapted to record images received by each camera of each of the M cameras and to calculate therefrom the position of each of the tools, and further adapted to provide automatically the results of the calculation to the human operator of the interface.

[0049] It is another object to disclose the method, additionally comprising steps of providing a real time image of said surgical environment using at least one endoscope.

[0050] It is another object to disclose the method, additionally comprising steps of selecting said tool to be an endoscope.

[0051] It is another object to disclose the method, additionally comprising steps of positioning at least one proximity sensor on the outer circumference of said tool.

[0052] It is another object to disclose the method, additionally comprising steps of selecting said instructions from a predetermined set of rules selected from a group consisting of: most used tool rule, right tool rule, left tool rule, field of view rule, no fly zone rule, a route rule, environmental rule, operator input rule, proximity rule; collision prevention rule, history-based rule, tool-dependent ALLOWED and RESTRICTED movements rule, preferred volume zone rule, preferred tool rule, movement detection rule, tagged tool rule, change of speed rule and any combination thereof.

[0053] It is another object to disclose the method, wherein said route rule comprises steps of: providing a communicable database; storing a predefined route in which said at least one surgical tool is adapted to move within said surgical environment; comprising said predefined route of n 3D spatial positions of said at least one surgical tool, n is an integer greater than or equal to 2; said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said n 3D spatial positions of said predefined route, and said RESTRICTED movements are movements in which said location of said at least one surgical tool is substantially different from said n 3D spatial positions of said predefined route.

[0054] It is another object to disclose the method, wherein said environmental rule comprises steps of: providing a communicable database; receiving at least one real-time image of said surgical environment in said communicable database; performing real-time image processing of the same and determining the 3D spatial position of hazards or obstacles in said surgical environment; determining said ALLOWED and RESTRICTED movements according to said hazards or obstacles in said surgical environment, such that said RESTRICTED movements are movements in which said at least one surgical tool is located substantially in at least one of said 3D spatial positions, and said ALLOWED movements are movements in which the location of said at least one surgical tool is substantially different from said 3D spatial positions.

[0055] It is another object to disclose the method, additionally comprising steps of selecting said hazards or obstacles in said surgical environment from a group consisting of tissue, a surgical tool, an organ, an endoscope and any combination thereof.

[0056] It is another object to disclose the method, wherein said operator input rule comprises steps of: providing a communicable database; and receiving input from an operator of said system regarding said ALLOWED and RESTRICTED movements of said at least one surgical tool.

[0057] It is another object to disclose the method, additionally comprising steps of: comprising said input of n 3D spatial positions, n is an integer greater than or equal to 2; defining at least one of said spatial positions as an ALLOWED location; defining at least one of said spatial positions as a RESTRICTED location; such that said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said at least one surgical tool is substantially different from said n 3D spatial positions.

[0058] It is another object to disclose the method, additionally comprising steps of: comprising said input of at least one rule according to which ALLOWED and RESTRICTED movements of said at least one surgical tool are determined, such that the spatial position of said at least one surgical tool is controlled by said controller according to said ALLOWED and RESTRICTED movements.

[0059] It is another object to disclose the method, additionally comprising steps of selecting said predetermined set of rules from a group consisting of: most used tool, right tool rule, left tool rule, field of view rule, no fly zone rule, route rule, environmental rule, operator input rule, proximity rule, collision prevention rule, preferred volume zone rule, preferred tool rule, movement detection rule, history-based rule, tool-dependent ALLOWED and RESTRICTED movements rule, and any combination thereof.

[0060] It is another object to disclose the method, wherein said operator input rule comprises steps of: converting an ALLOWED movement to a RESTRICTED movement and converting a RESTRICTED movement to an ALLOWED movement.

[0061] It is another object to disclose the method, wherein said proximity rule comprises steps of: defining a predetermined distance between at least two surgical tools; said ALLOWED movements are movements which are within the range or out of the range of said predetermined distance, and said RESTRICTED movements are movements which are out of the range or within the range of said predetermined distance.

[0062] It is another object to disclose the method, wherein said proximity rule comprises steps of: defining a predetermined angle between at least three surgical tools; said ALLOWED movements are movements which are within the range or out of the range of said predetermined angle, and said RESTRICTED movements are movements which are out of the range or within the range of said predetermined angle.

[0063] It is another object to disclose the method, wherein said collision prevention rule comprises steps of: defining a predetermined distance between said at least one surgical tool and an anatomical element within said surgical environment; said ALLOWED movements are movements which are in a range that is larger than said predetermined distance, and said RESTRICTED movements are movements which is in a range that is smaller than said predetermined distance.

[0064] It is another object to disclose the method, additionally comprising steps of selecting said anatomical element from a group consisting of tissue, organ, another surgical tool and any combination thereof.

[0065] It is another object to disclose the method, wherein at least one of the following is being held true (a) additionally providing an endoscope for said system; and provide at least one real-time image of said surgical environment by means of said endoscope; (b) selecting at least one of said surgical tools to be an endoscope and providing at least one real-time image of said surgical environment by means of said endoscope.

[0066] It is another object to disclose the method, wherein said right tool rule comprises steps of: determining said ALLOWED movement of said endoscope according to the movement of the surgical tool positioned to right of said endoscope; further wherein said left tool rule comprises steps of: determining said ALLOWED movement of said endoscope according to the movement of the surgical tool positioned to left of said endoscope.

[0067] It is another object to disclose the method, wherein said tagged tool rule comprises steps of: tagging at least one surgical tool within said surgical environment and determining said ALLOWED movements of said endoscope to be movements that constantly track the movement of said tagged surgical tool.

[0068] It is another object to disclose the method, wherein said field of view rule comprises steps of: providing a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; generating a field of view from the combination of all of said n 3D spatial positions; maintaining a constant field of view by determining said ALLOWED movement of said endoscope to be within said n 3D spatial positions, such that said ALLOWED movements are movements in which said endoscope is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said endoscope is substantially different from said n 3D spatial positions.

[0069] It is another object to disclose the method, wherein said preferred volume zone rule comprises steps of: providing a communicable database comprising n 3D spatial positions;

n is an integer greater than or equal to 2; generating said preferred volume zone from said n 3D spatial positions; determining said ALLOWED movement of said endoscope to be within said n 3D spatial positions and said RESTRICTED movement of said endoscope to be outside said n 3D spatial positions, such that said ALLOWED movements are movements in which said endoscope is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said endoscope is substantially different from said n 3D spatial positions.

[0070] It is another object to disclose the method, wherein said preferred tool rule comprises steps of: providing a communicable database, storing a preferred tool in said database; determining said ALLOWED movement of said endoscope so as to constantly track the movement of said preferred tool.

[0071] It is another object to disclose the method, wherein said no fly zone rule comprises steps of: providing a communicable database comprising n 3D spatial positions, n is an integer greater than or equal to 2; defining a predetermined volume within said surgical environment from said n 3D spatial positions; determining said RESTRICTED movement to be said movement within said no fly zone; determining said ALLOWED movement to be said movement outside said no fly zone, such that said RESTRICTED movements are movements in which said at least one of said surgical tool is located substantially in at least one of said n 3D spatial positions, and said ALLOWED movements are movements in which the location of said at least one endoscope is substantially different from said n 3D spatial positions.

[0072] It is another object to disclose the method, wherein said most used tool rule comprises steps of: providing a communicable database; counting the amount of movement of each said surgical tool; constantly positioning said endoscope to track movement of the most moved surgical tool.

[0073] It is another object to disclose the method, additionally comprising steps of providing a maneuvering subsystem communicable with said controller, spatially repositioning said at least one surgical tool during a surgery according to said predetermined set of rules; and alerting the physician of said RESTRICTED movement of said at least one surgical tool.

[0074] It is another object to disclose the method, additionally comprising steps of selecting said alert from a group consisting of: audio signaling, voice signaling, light signaling, flashing signaling and any combination thereof.

[0075] It is another object to disclose the method, additionally comprising steps of defining said ALLOWED movement as a movement permitted by said controller and defining said RESTRICTED movement as a movement denied by said controller.

[0076] It is another object to disclose the method, wherein said history-based rule comprises steps of: providing a communicable database storing each 3D spatial position of each said surgical tool, such that each movement of each surgical tool is stored; determining said ALLOWED and RESTRICTED movements according to historical movements of said at least one surgical tool, such that said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said 3D spatial positions, and said RESTRICTED movements are movements in which the location of said at least one surgical tool is substantially different from said n 3D spatial positions.

[0077] It is another object to disclose the method, wherein said tool-dependent ALLOWED and RESTRICTED movements rule comprises steps of: providing a communicable database; storing predetermined characteristics of at least one said surgical tool; determining said ALLOWED and RESTRICTED movements according to said predetermined characteristics of said surgical tool; such that ALLOWED movements are movements of said endoscope which track said surgical tool having said predetermined characteristics.

[0078] It is another object to disclose the method, additionally comprising steps of selecting said predetermined characteristics of said surgical tool from a group consisting of: physical dimensions, structure, weight, sharpness, and any combination thereof.

[0079] It is another object to disclose the method, wherein said movement detection rule comprises steps of: providing a communicable database comprising the real-time 3D spatial positions of each said surgical tool; detecting movement of said at least one surgical tool when a change in said 3D spatial positions is received, such that said ALLOWED movements are movements in which said endoscope is re-directed to focus on said moving surgical tool.

[0080] It is another object to disclose the method, additionally comprising steps of providing a maneuvering subsystem communicable with said controller, spatially repositioning said at least one surgical tool during a surgery according to said predetermined set of rules, such that if said movement of said at least one surgical tool is a RESTRICTED movement, said maneuvering subsystem prevents said movement.

[0081] It is another object to disclose the method, additionally comprising steps of comprising said at least one location estimating means of at least one endoscope adapted to acquire real-time images of said surgical environment within said human body; providing at least one surgical instrument spatial location software; receiving said real-time images of said surgical environment from said endoscope and estimating said 3D spatial position of said at least one surgical tool using said spatial location software.

[0082] It is another object to disclose the method, additionally comprising steps of providing said at least one location estimating means comprising (a) at least one element selected from a group consisting of optical imaging means, radio frequency transmitting and receiving means, at least one mark on said at least one surgical tool and any combination thereof; and, (b) at least one surgical instrument spatial location software adapted to estimate said 3D spatial position of said at least one surgical tool by means of said element.

[0083] It is another object to disclose the method, additionally comprising steps of selecting said at least one location estimating means to be an interface subsystem between a surgeon and said at least one surgical tool, the interface subsystem comprising:

[0084] a. at least one array comprising N regular or pattern light sources, where N is a positive integer;

[0085] b. at least one array comprising M cameras, each of the M cameras, where M is a positive integer;

[0086] c. optional optical markers and means for attaching the optical marker to the at least one surgical tool; and;

[0087] d. a computerized algorithm operable via the controller, the computerized algorithm adapted to record images received by each camera of each of the M cameras and to calculate therefrom the position of each of the tools, and further adapted to provide automatically the results of the calculation to the human operator of the interface.

[0088] It is another object of the present invention to disclose the surgical controlling system, wherein said articulating tool has articulations substantially at the tip of said tool, substantially along the body of said too, and any combination thereof.

[0089] It is another object of the present invention to disclose the surgical controlling system, wherein control of articulation is selected from a group consisting of hardware control, software control and any combination thereof.

[0090] It is another object of the present invention to disclose the surgical controlling system, wherein said tool has articulation in a regions selected from a group consisting of near the tip of said tool, on the body of said tool, and any combination thereof.

[0091] It is another object of the present invention to disclose the method, additionally comprising steps of providing said tool with articulations substantially at the tip of said tool, substantially along the body of said too, and any combination thereof.

[0092] It is another object of the present invention to disclose the method, additionally comprising steps of controlling articulation by means of a method selected from a group consisting of hardware control, software control and any combination thereof.

[0093] It is another object of the present invention to disclose the method, additionally comprising steps of providing a tool articulated at a region selected from a group consisting of near the tip of said tool, on the body of said tool, and any combination thereof.

BRIEF DESCRIPTION OF THE FIGURES

[0094] In order to understand the invention and to see how it may be implemented in practice, and by way of non-limiting example only, with reference to the accompanying drawing, in which

[0095] FIG. **1** schematically illustrates a structured light system;

[0096] FIGS. **2**A-**2**H illustrate binary coded patterns;

[0097] FIGS. **3**A-**3**H illustrate Gray-coded patterns;

[0098] FIG. **4** shows a stripe pattern of varying intensity;

[0099] FIG. **5** shows the sensitivity of the reconstructed object point to perturbations for an embodiment of the system for an embodiment of the system;

[0100] FIG. **6**A-D depicts I_H, I_L, the MSB pattern and the LSB pattern for an embodiment of the system;

[0101] FIG. **7**A-E shows the raw image corresponding to one embodiment of a stripe pattern, the normalized intensity image for that stripe pattern, the binary image for that stripe pattern, the fidelity image for that stripe pattern and profiles of a vertical line from the normalized intensity image for an embodiment of the system;

[0102] FIGS. **8**A and **8**B show the decoded stripe code T of a scanned object and the fidelity image F for an embodiment of the system;

[0103] FIG. **9** depicts images of a human face reconstructed using an embodiment of the system;

[0104] FIGS. **10**-**10**C depict the reconstructed surface and a vertical profile of the Z-map for an embodiment of the system;

[0105] FIG. **11** illustrates an embodiment of a calibration object;

[0106] FIG. **12** depicts forward projections of the theoretically calculated calibration object fiducial points for an embodiment of the system;

[0107] FIGS. **13**A-**13**D show profiles of a reconstructed calibration object for an embodiment of the system;

[0108] FIG. **14** schematically illustrates a laparoscopic system using structured light for generating 3D images;

[0109] FIG. **15** schematically illustrates an embodiment of the distal end of an endoscope;

[0110] FIG. **16** shows a plot of errors in pixel coordinates for a typical calibration configuration;

[0111] FIG. **17** shows a stem plot of errors for a typical calibration configuration;

[0112] FIG. **18** shows an embodiment of a calibration object;

[0113] FIG. **19** shows a plot of pixel residuals;

[0114] FIG. **20** shows a plot of stripe residuals; and

[0115] FIG. **21** shows a plot of spatial intersection errors

[0116] FIG. **22** shows absorption of light by substances found in tissue;

[0117] FIGS. **23**-**25** show absorption of light by tissue at different wavelengths;

[0118] FIG. **26** depicts a direction indicator;

[0119] FIG. **27** presents a means to control the articulation of an articulating endoscope;

[0120] FIGS. **28**A and **28**B illustrate the use of the endoscope articulation control;

[0121] FIG. **29** illustrates articulation of the endoscope;

[0122] FIGS. **30**A-**30**D illustrate one embodiment of the present invention;

[0123] FIG. **31**A-D schematically illustrates operation of an embodiment of a tracking system with collision avoidance system;

[0124] FIG. **32**A-D schematically illustrates operation of an embodiment of a tracking system with no fly zone rule/function;

[0125] FIG. **33**A-D schematically illustrates operation of an embodiment of a tracking system with preferred volume zone rule/function;

[0126] FIG. **34** schematically illustrates operation of an embodiment of the organ detection function/rule;

[0127] FIG. **35** schematically illustrates operation of an embodiment of the tool detection function/rule;

[0128] FIG. **36**A-B schematically illustrates operation of an embodiment of the movement detection function/rule;

[0129] FIG. **37**A-D schematically illustrates operation of an embodiment of the prediction function/rule;

[0130] FIG. **38** schematically illustrates operation of an embodiment of the right tool function/rule;

[0131] FIG. **39**A-B schematically illustrates operation of an embodiment of the field of view function/rule;

[0132] FIG. **40** schematically illustrates operation of an embodiment of the tagged tool function/rule;

[0133] FIG. **41**A-C schematically illustrates operation of an embodiment of the proximity function/rule;

[0134] FIG. **42**A-B schematically illustrates operation of an embodiment of the operator input function/rule;

[0135] FIGS. **43**A-D schematically illustrate an embodiment of a tracking system with a constant field of view rule/function;

[0136] FIG. **44** schematically illustrates an embodiment of a tracking system with a change of speed rule/function;

[0137] FIGS. **45**A and **45**B schematically illustrate movement of an articulated tool; and

[0138] FIG. **46** schematically illustrates movement of an articulated tool.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0139] The following description is provided, alongside all chapters of the present invention, so as to enable any person skilled in the art to make use of said invention and sets forth the best modes contemplated by the inventor of carrying out this invention. Various modifications, however, will remain apparent to those skilled in the art, since the generic principles of the present invention have been defined specifically to provide a means and method for directing a laparoscopic system comprising at least one articulating tool, where the laparoscopic system uses structured light to provide a 3D image of the field of view using a single camera.

[0140] The term 'articulation' refers hereinafter to any device which has more than 1 degree of freedom. Thus, said tool can bend either in the tip thereof or any location in the body of the same.

[0141] The term 'toggle' refers hereinafter to switching between one tagged surgical tool to another.

[0142] The term 'surgical environment' refers hereinafter to any anatomical part within the human body which may be in surrounding a surgical instrument. The environment may comprise: organs, body parts, walls of organs, arteries, veins, nerves, a region of interest, or any other anatomical part of the human body.

[0143] The term 'endoscope' refers hereinafter to any means adapted for looking inside the body for medical reasons. This may be any instrument used to examine the interior of a hollow organ or cavity of the body. The endoscope may also refer to any kind of a laparascope. It should be pointed that the following description may refer to an endoscope as a surgical tool.

[0144] The term 'region of interest' refers hereinafter to any region within the human body which may be of interest to the operator of the system of the present invention. The region of interest may be, for example, an organ to be operated on, a RESTRICTED area to which approach of a surgical instrument is RESTRICTED, a surgical instrument, or any other region within the human body.

[0145] The term 'spatial position' refers hereinafter to a predetermined spatial location and/or orientation of an object (e.g., the spatial location of the endoscope, the angular orientation of the endoscope, and any combination thereof).

[0146] The term 'prohibited area' refers hereinafter to a predetermined area to which a surgical tool (e.g., an endoscope) is prohibited to be spatially positioned in.

[0147] The term 'preferred area' refers hereinafter to predetermined area to which a surgical tool (e.g., an endoscope) is allowed and/or preferred to be spatially positioned in.

[0148] The term 'automated assistant' refers hereinafter to any mechanical device (including but not limited to a robotic device) that can maneuver and control the position of a surgical or endoscopic instrument, and that can in addition be adapted to receive commands from a remote source.

[0149] The term 'tool' or 'surgical instrument' refers hereinafter to any instrument or device introducible into the human body. The term may refer to any location on the tool. For example it can refer to the tip of the same, the body of the same and any combination thereof. It should be further pointed that the following description may refer to a surgical tool/instrument as an endoscope.

[0150] The term 'provide' refers hereinafter to any process (visual, tactile, or auditory) by which an instrument, computer, controller, or any other mechanical or electronic device can report the results of a calculation or other operation to a human operator.

[0151] The term 'automatic' or 'automatically' refers to any process that proceeds without the necessity of direct intervention or action on the part of a human being.

[0152] The term 'ALLOWED movement' refers hereinafter to any movement of a surgical tool which is permitted according to a predetermined set of rules.

[0153] The term 'RESTRICTED movement' refers hereinafter to any movement of a surgical tool which is forbidden according to a predetermined set of rules. For example, one rule, according to the present invention, provides a preferred volume zone rule which defines a favored zone within the surgical environment. Thus, according to the present invention an ALLOWED movement of a surgical tool or the endoscope is a movement which maintains the surgical tool within the favored zone; and a RESTRICTED movement of a surgical tool is a movement which extracts (or moves) the surgical tool outside the favored zone.

[0154] The term 'time step' refers hereinafter to the working time of the system. At each time step, the system receives data from sensors and commands from operators and processes the data and commands and executes actions. The time step size is the elapsed time between time steps.

[0155] The term 'proximity sensor' hereinafter refers to a sensor able to detect the presence of nearby objects without physical contact. Proximity sensors are sometimes referred to as 'force sensors'. A proximity sensor often emits an electromagnetic field or a beam of electromagnetic radiation (infrared, for instance), and looks for changes in the field or return signal. The object being sensed is often referred to as the proximity sensor's target. Different proximity sensor targets demand different sensors. For example, a capacitive photoelectric sensor might be suitable for a plastic target; an inductive proximity sensor always requires a metal target. Proximity sensors can be introduced into the body and used for detecting metal fragments during surgery. See, for example, Sakthivel, M., *A new inductive proximity sensor as a guiding tool for removing metal shrapnel during surgery*, Instrumentation and Measurement Technology Conference (I2MTC), 2013 IEEE International, pp. 53-57. ISSN: 1091-5281, print ISBN: 978-1-4673-4621-4. INSPEC Accession Number: 13662555.

[0156] The term 'degrees of freedom' (DOF) refer hereinafter to a set of independent displacements that specify completely the displaced position of the endoscope or laparoscope.

[0157] The term 'insertion point' refers hereinafter to the point where the endoscope enters the human body.

[0158] The term 'camera' hereinafter refers to an image-capture device, capable of creating a 2D image of an object. Examples of a camera include, but are not limited to, a CCD array and an electromagnetic system such as a TV camera.

[0159] The term 'endoscope distal end' hereinafter refers to the end of the endoscope that is inside the patient.

[0160] The term 'endoscope proximal end' hereinafter refers to the end of the camera outside the patient. The camera is attached to the endoscope's proximal end.

[0161] The term 'structured light' hereinafter refers to a method of producing 3D images using a single 2D camera. In the structured light method, the object is illuminated by a set of rays of light, each ray illuminating a spot on the object from a known position and a known direction, and each ray emitted at a known time. For each known time, a 2D camera image is created from light reflected from the spots created from rays existing at that time. Initially, a known calibration object is illuminated. From the known shape, size and position of the calibration object and from the locations in the camera images of the reflected light, mathematical matrices can be calculated. These matrices enable calculation of the 3D location of the surface of an unknown object, when the unknown object is illuminated by the same set of rays as illuminated the calibration object.

[0162] The term 'structured light pattern' hereinafter refers to the set of rays of light with a known spatial and temporal pattern used, as described above, to illuminate an object.

[0163] The term 'field of view' (FOV) hereinafter refers to the scene visible to the camera.

[0164] The terms 'about' and 'approximately' hereinafter refers to a range of ±20% of the value.

[0165] The term 'world' hereinafter refers to the region of space in which objects are located.

[0166] The term 'world coordinates' hereinafter refers to a coordinate system fixed in the world. The location in space of a physical object to be imaged will be described by the world coordinate system.

[0167] The term 'projector' hereinafter refers to the set of light rays used to illuminate an object.

[0168] The term 'projector coordinates' hereinafter refers to a coordinate system in which the projector is located and which describes the relation of the light rays to each other, both spatially and temporally.

[0169] The term 'camera coordinate system' hereinafter refers to a coordinate system fixed with respect to the camera.

[0170] The term 'stripe id' hereinafter refers to the temporal and spatial location and direction of a light ray.

[0171] Laparoscopic surgery, also called minimally invasive surgery (MIS), is a modern surgical technique in which operations in the abdomen are performed through small incisions (usually 0.5-1.5 cm) as compared to larger incisions needed in traditional surgical procedures. The key element in laparoscopic surgery is the use of a laparoscope, which is a device adapted for viewing the scene within the body, at the distal end of the laparoscope. Either an imaging device is placed at the end of the laparoscope, or a rod lens system or fiber optic bundle is used to direct this image to the proximal end of the laparoscope. Also attached is a light source to illuminate the operative field, inserted through a 5 mm or 10 mm cannula or trocar to view the operative field.

[0172] The abdomen is usually injected with carbon dioxide gas to create a working and viewing space. The abdomen is essentially blown up like a balloon (insufflated), elevating the abdominal wall above the internal organs like a dome. Within this space, various medical procedures can be carried out.

[0173] In many cases, the laparoscope cannot view the entire working space within the body, so the laparoscope is repositioned to allow the surgeon to view regions of interest within the space. In some laparoscopic system, this requires the surgeon to instruct an assistant to manually move the laparoscope. In other systems, the surgeon himself instructs the laparoscope to move, by a manual control system such as a button, joystick or slider attached to the surgeon or to a surgical tool, by contact with a touchscreen, or by voice commands.

[0174] In all such systems, in directing and maneuvering the surgical controlling system, the controller needs to avoid obstacles such as body organs and tools or other surgical equipment in the body cavity. Its speed should be controlled so that, on the one hand, the speed is low enough to make avoidance routine and to ensure that the instrument accurately reaches the desired location and, on the other hand, the speed needs to be great enough that maneuvers are accomplished in a reasonable time.

[0175] In order to avoid the obstacles, in a conventional system, the endoscope must be routed around them, increasing the complexity of maneuvering and the time taken for maneuvering.

[0176] In the present, system, the system comprises at least one articulating section, typically an articulating tool such as an articulating endoscope. The articulating tool can have an articulating tip, where the articulations are near the tip, it can have an articulating body, where the articulations are in the body or shaft of the tool, or both. The articulations allow bending in at least two degrees of freedom (DOF), preferably in four DOF, and possibly in all six DOF (bending in all three directions and rotating in all three directions).

[0177] In comparison to a rigid tool, during maneuvering, an articulating tool can use more direct routes, as the articulating section enables removal of the tip of an articulating tool from the region of an obstacle. For example, instead of routing an endoscope around a body organ, the endoscope can articulate such that its tip is withdrawn to a sufficient height that the route of the endoscope can be directly across the organ.

[0178] Furthermore, the system has more flexibility in positioning. For example, the angle of the field of view can be changed by changing the articulation of the endoscope, with only minimal change of the position of the main part of the endoscope.

[0179] A device of the present invention, with an articulating endoscope and providing a 3D image, is useful for colonoscopy or gastroscopy, treatments where the endoscope moves within a relatively restricted, non-straight space. By traversing the interior of a portion of the alimentary canal, abnormalities such as, but not limited to, polyps or ulcers can be identified and a warning provided to a user of the system and to the patient. In preferred embodiments, the system additionally comprises recognition software that can identify abnormalities and can label the abnormality in real time on an image of the field of view. The label can be by any means known in the art such as, but not limited to, text, a colored patch, a textured patch, an arrow or other marker, and any combination thereof.

[0180] Because of the flexibility provided by the articulating endoscope and because of the increased locatability possible with a 3D image, the device of the present invention, compared to the prior art, can more easily follow the contours of body organs and can more effectively view the sides and backs of organs. It can therefore find cysts, lumps or other abnormal masses in the abdominal cavity more effectively than the prior art. It can also efficiently map the interior of the abdominal cavity and can be used for cartography of the intestines, including the bowels and colon.

[0181] In many cases, the surgeon wants a close-up view of his working area; in other cases an overview is desirable, and a rapid transition from close-up to overview and vice-versa can also be desirable.

[0182] The device disclosed herein uses a standard laparoscopic camera and a computer-controllable laparoscopic light source in conjunction with software using the structured light method in order to provide a laparoscopic system which presents the user with 3D images from a single camera.

[0183] The advantages of a 3D image include:

[0184] It increases the accuracy and reliability of tool detection and tracking from the laparoscope image, thereby minimizing or eliminating the need for auxiliary equipment for the purpose.

[0185] It increases the accuracy of navigation within the body cavity, thereby minimizing the risk of inadvertent tissue damage.

[0186] It provides a three-dimensional display for the surgeon, thereby increasing the accuracy with which he can work.

[0187] There are many methods of providing a 3D image. These include, but are not limited to:

[0188] Use of two cameras to provide a stereo image. This has the disadvantage that two separated sets of camera lenses are needed, and therefore a laparoscope adapted to accept two separated camera lenses.

[0189] Use of the motion of the camera to get more than one view of the scene, each view from a different perspective, and then combining the views via internal algorithms. This has the disadvantage of requiring motion of the camera.

[0190] Use of the Structured Light technique. This requires calibration of the system before use, and can be sensitive to spurious pixels in the image, but has the advantage of requiring neither camera motion nor a special laparoscope.

[0191] For the laparoscope disclosed herein, structured light is the preferred method of providing a 3D image.

[0192] Advantages of a structured light system include:

[0193] The accuracy of the three-dimensional reconstruction is very high.

[0194] Recovery from bit errors is possible.

[0195] It is possible to provide 3D images of bodies of uniform shade, which is not possible in a stereo system using two cameras.

[0196] Adding a Distance Index from one object to the other (e.g., tissue).

[0197] Measurement of distances between any two points in the image is simple, since the distance is a geodesic distance over the surface or the Euclidean distance.

[0198] It is possible to embed texture in the image, improving the ease of identification of tissues.

[0199] It is possible to use a standard camera and a standard laparoscope, lighting the object via a standard laparoscope lighting system.

[0200] A high resolution camera can provide sufficient detail to create a detailed 3D image.

[0201] In some embodiments, a wide-angle lens such as, but not limited to, a fish-eye lens, an omnidirectional lens and any combination thereof provides an image of a large portion, if not all, of the working area, such as the interior of the abdomen. The image provided by a wide-angle lens is frequently distorted; in preferred embodiments of systems with a wide-angle lens, software is used to correct the distortion.

[0202] In the structured light technique, schematically illustrated (**100**) in FIG. **1**, a controlled light pattern or a series of controlled light patterns is emitted by a light source (**110**) and the 3D image is constructed from the light pattern received by a sensor (**120**) after reflection from an object (**130**) or objects illuminated by the light and in the field of view of the sensor.

[0203] In the simplest structured light camera, a "projector", a source of light, projects a spot of light, for example, a laser beam, onto an object. The location of the projector and the direction of projection are known. The location on the camera image of the reflected spot can be easily located and identified. Since the point location on both the projector and the camera is known, reconstruction of the coordinates in space of the reflecting point on the object (the "shape world coordinates") can be carried out by simple triangulation.

[0204] A more efficient scheme replaces the point laser beam by a line beam that "sweeps" the object. Still, sweeping the entire scene by a laser beam is a time consuming operation and therefore is limited to static objects.

[0205] For a better scan time, several stripe illumination-based techniques have been proposed. Single pattern approaches, using spatial encoding of projection planes or rays can be used. Although time-efficient, spatial encoding generally produces a sparse depth map with mediocre spatial resolution.

[0206] High reliability identification of projection planes with non-restrictive assumptions on scene contents and illumination conditions can be achieved by temporal encoding, which is based on projection of a sequence of light patterns ("stripes") onto the object. A robust, commonly used structured light system based on binary light patterns encoded with Gray code is used in preferred embodiments of the device disclosed herein. Color modulation, which allows a reduction in the number of stripes projected onto the object, is also possible, with a color camera. Color modulation, as discussed hereinbelow, can also be used be used in addition to spatial and temporal encoding in order to determine the nature of the tissues being imaged,

[0207] FIG. **2**A-H shows binary coded patterns, while FIG. **3**A-H shows Gray-coded patterns. In both figures, 'HSB' is the highest significant bit, and 'LSB' is the least significant bit. The patterns differ in that, in the Gray-coded patterns, the edge-most light stripe is split, appearing at both edges, so that the pattern is symmetrical about its center. Having a (half) light stripe at each edge improves the robustness of the system.

[0208] An important issue in structured light systems is calibration. Reconstruction is possible only when the camera projection matrix and the projection planes are known in the world coordinate system. Calibration of structured light scanners is usually more complicated than that of a passive stereo pair. A standard approach consists of three steps: estimating the camera intrinsic matrix (camera calibration), estimating the plane equations for each of the projection planes (projector calibration) and finally, estimating the Euclidean transformation between the camera and the projector (projector-camera calibration).

[0209] Other examples of structured light systems use stripes that vary in intensity across the stripe, with each stripe being black at one edge and white at the other. In embodiments with varying intensity, the intensity changes in time as the plane of light is swept across the working space which includes the object. FIG. **4**A-B shows the intensity of the light as a function of time t, with t_1 the period of the stripe pattern of FIG. **4**A and t_2 the period of the stripe pattern of FIG. **4**B.

Example 1

[0210] An alternative approach, however, provides the preferred embodiment for the present invention. This alternative approach is based on estimation of the world to camera image and world-to-projector coordinate system transformation, extended to simultaneously estimating a backprojection operator, an operator that enables determination of the location in space of the surface of an object, from the locations on camera images of spots of light reflected from the object, where the spots of light are generated by rays emitted from known positions, in known directions and at known times.

[0211] The following sections describe a method of determining the backprojection operator. In the method described hereinbelow, a calibration object of known shape and size (the world object) is illuminated by a set of rays of light (the projector, in the projector coordinate system) emitted from known positions, in known directions and at known times. These rays are reflected from the calibration object (the object, in the world coordinate system) and generate at least one 2D camera image (the camera image, in the camera coordinate system). From the known ray positions, the known spot positions on the camera images and the known shape and size of the calibration object, operators are determined that enable determination of the 3D position in space of an unknown object.

[0212] In the derivation hereinbelow, the model will be described, then a method of generating a 3D image of an object (reconstruction of the object) from the camera images and the stability of the reconstruction will be described. This is followed by a method of generating the reconstruction operators from a calibration object, and an implementation of an embodiment of the method.

[0213] Model of a Structured Light System

[0214] A typical structured light system consists of a camera and a projector. The role of the projector is to light the scanned object in such a way that, from the image (or sequence of images) acquired by the camera, a stripe code can be extracted. The encoding can be done either spatially using a single pattern or temporally using a series of varying patterns. The raw output of a structured light scanner is a stripe code assigned for every pixel in the image. Intersection of a ray in world coordinate system (WCS) with a plane in WCS yields the world coordinates of an object point. Using this triangulation method, the raw sensor data is converted into 3D data in the WCS.

[0215] For simplicity, in the derivations below, it will be assumed that both the camera and the projector obey the pin-hole optical model (non-linear distortion correction can be applied for lenses that do not obey this model). The transformation from 3D world coordinates to camera image plane coordinates will be described by a 3×4 perspective projection matrix (PPM). The projector will be modeled by a 2×4 PPM, mapping world coordinates to stripe identification code (id).

[0216] Three coordinate systems are defined: a homogenous world coordinate system X_w in which the object's position is specified; a homogenous camera coordinate system X_c, in which pixel locations in the image plane are specified, and a homogenous projector coordinate system X_p, in which stripe ids are specified. The latter is particular, since it contains only one independent coordinate.

[0217] The transformation from world coordinates to camera coordinates is given by

$$X_c = C_c X_w, \tag{1}$$

where C_c is the camera PPM and is of the form

$$C_c = \alpha \begin{bmatrix} f_x & kf_y & x_c^0 \\ 0 & f_y & y_c^0 \\ 0 & 0 & 1 \end{bmatrix} [\, R_c \quad t_c \,]. \tag{2}$$

[0218] The rotation matrix R_c and the translation vector t_c define the transformation between WCS X_w and the camera-centric reference frame X_c. The parameters f_x and f_y are the camera focal length scaled to each of the CCD dimensions, and x_c^0 and y_c^0 are the origin of X_c in image coordinates. The parameter α is a proportion coefficient and k is the shear of the camera coordinate system.

[0219] Similarly, the transformation form world coordinates to projector coordinates is given by

$$X_p = C_p X_w, \tag{3}$$

where C_p is the projector PPM of the form

$$C_p = \alpha \begin{bmatrix} f_p & 0 & x_p^0 \\ 0 & 0 & 1 \end{bmatrix} [\, R_p \quad t_p \,] \tag{4}$$

[0220] R_p, and t_p define the transformation between WCS and X_p. The parameter f_p is the projector focal length scaled to the projector's dimensions, and x_p^0 is the origin of X_p in projector coordinates, which physically is the x-coordinate of the intersection of the optical axis and the projector.

[0221] Here we implicitly assume that the stripe code varies along the horizontal direction of the projector. McIvor and Valkenburg [A. M. McIvor, R. J. Valkenburg, I Robert, J. Valkenburg, J. Valkenburg, Calibrating a structured light system, Image & Vision Computing, New Zealand, 1995] show that C_p is a valid camera PPM if and only if the submatrix formed by its first three columns has full rank. Similarly, P_p is a valid projector PPM if and only if the submatrix formed by its first three columns is of rank **2**.

[0222] Equations 1 and 3 define the transformation

$$T: X_w \rightarrow (X_c, X_p), \tag{5}$$

which maps an object point in WCS into pixel location in the camera image plane and a stripe id (coordinate in the projector system of coordinates). We refer to this transformation as forward projection.

[0223] The world coordinates of the object point are usually unknown and have to be determined, whereas the pair (x_c, x_p) is what the structured light sensor measures and can be extracted from the raw data. Therefore, given the camera and the projector PPMs and a pair of measurements (x_c, x_p), one can attempt inverting eq. (5) in order to calculate x_w. We will term the inverse transformation

$$T^{-1}: (X_c, X_p) \rightarrow X_w, \tag{6}$$

as backprojection and the process of determining world coordinates from measured data as reconstruction.

[0224] Reconstruction requires the knowledge of C_c and C_p. Therefore, calibration must be performed before, during which the forward projection operator is estimated. This is done by measuring a set of pairs $\{(x_c, x_p)_n\}_{n=1}^N$ corresponding to a set of points with known world coordinates $\{(x_c)_n\}_{n=1}^N$. Physically, a calibration object with a set of fiducial points, whose location is known, is scanned. WCS is then chosen to be some local coordinate system of the calibration object, in which the coordinates of each fiducial point are specified.

[0225] Reconstruction

[0226] In this section we assume that the forward projection operator T is known (i.e. the projective matrices C_c and C_p are given). The reconstruction problem can be stated as follows: given measured (x_c, x_p), calculate x_w according to

$$x_w=T^{-1}(x_c,x_p). \tag{7}$$

[0227] Explicitly, x_w has to satisfy the linear system of equations

$$x_c=C_cx_w \tag{8}$$

$$x_p=C_px_w. \tag{9}$$

[0228] However, since all vectors are given in homogenous coordinates, it is possible that no x_w satisfies eqs. (8) and (9) simultaneously. Let us denote $x_c=[w_cx_c,w_cy_c,w_c]^T$ and $x_p=[w_px_p,w_p]^T$ and let ck, pk be the k-th row of C_c and C_p, respectively. Then, the linear system of equations can be rewritten as

$$w_cx_c=c_1x_w$$

$$w_cy_c=c_2x_w$$

$$w_c=c_3x_w \tag{10}$$

and

$$w_px_p=p_1x_w$$

$$w_p=p_2x_w. \tag{11}$$

[0229] Substituting w_c into eq. (10) and wp into eq. (11) yields

$$x_cc_3x_w=c_1x_w$$

$$y_cc_3x_w=c_2x_w$$

$$x_pp_2x_w=p_1x_w, \tag{12}$$

which can be written in matrix notation as $Qx_w=0$, where

$$Q=\begin{bmatrix} x_cc_3-c_1 \\ y_cc_3-c_2 \\ x_pp_2-p_1 \end{bmatrix} \tag{13}$$

[0230] The matrix Q can be split into a 3×3 matrix R and a 3×1 vector s: Q=[R, s]. Substituting $x_w=[w_wx_w,w_wy_w,w_wz_w,w_w]^T$ yields

$$[R,s]\begin{bmatrix} w_wx_w \\ w_wx_y \\ w_wz_w \\ w_w \end{bmatrix}=R\begin{bmatrix} w_wx_w \\ w_wx_y \\ w_wz_w \end{bmatrix}+w_ws=0. \tag{14}$$

[0231] Therefore, the object point in non-homogenous world coordinates $x_w=[x_w,y_w,z_w]^T$ is a solution of the linear system

$$Rx_w=-s. \tag{15}$$

[0232] Backprojection is therefore given by

$$x_w=-R^{-1}s. \tag{16}$$

[0233] It must be remembered that both R and s are functions of x_c, y_c and x_p.

[0234] If C_c and C_p are valid camera and projector PPMs, R is invertible except of cases where the ray originating from the camera focal point to the object point is parallel to the plane originating at the projector focal point and passing through the object point. The latter case is possible either when the object point is located at infinity, or when the camera and the projector optical axes are parallel (this happens when $R_c=R_p$). This gives a constraint on camera and projector mutual location: in order to make triangulation possible, the camera should not have its optical axis parallel to that of the projector.

[0235] Reconstruction Stability

[0236] As discussed hereinabove, the matrix R in Eq. (15) becomes singular when the ray in the camera coordinate system and the plane in the projector coordinates system are parallel. A reasonable question that may arise is how stable is the solution under random perturbations of x_c and x_p. In this work, we will address only perturbations in x_i), since they are the most problematic ones in structured light systems.

[0237] For simplicity, let us assume that WCS coincides with the camera coordinate system and the transformation to the projector coordinate system is given by

$$x_p=R_p+t_p. \tag{17}$$

[0238] Without loss of generality, it can be assumed that the centers of the camera coordinate system and the projector coordinate system coincide with their optical axes, i.e. $x_c^0=y_c^0=x_p^0=0$. Without loss of generality, it can be assumed that the object point is found on some ray in $x_c=\alpha v_c$; the ray is uniquely defined by the camera image plane coordinates x_c and the point location is uniquely defined by the parameter α. The stripe id corresponding to the given object point can be denoted by x_p. Then, the following system of linear equations

$$n^Tx_p=0$$

$$n^T(R_px_c+t_p)=0, \tag{18}$$

must hold simultaneously; n denotes the normal to the plane defined by the stripe id x_p. Substituting $x_c=\alpha v_c$ yields

$$n^Tx_p=n^T(\alpha R_pv_c+t_p), \tag{19}$$

hence

$$\alpha=\frac{n^Tx_p}{n^TR_pv_c}. \tag{20}$$

[0239] However, in practice, the stripe id x_p is estimated using structured light, and therefore it is especially sensitive to noise. Let us assume that instead of the real stripe id x_p, a perturbed stripe id $\tilde{x}_p=x_p+\delta x_p$ was measured. This, in turn, means that $\tilde{x}_p=x_p+[\delta x_p,0,f_p]^T$, which yields

$$\tilde{\alpha}=\frac{n^T\tilde{x}_p}{n^TR_pv_c}. \tag{21}$$

[0240] Hence, the perturbation in x_p causes a perturbation in the location of the object point along the ray $x_c=\alpha v_c$ by

$$\delta\alpha = \frac{n_1 \delta x_p}{\|n\|_2 \|v\|_2 \sin\Theta_{nv}}, \tag{22}$$

where Θ_{nv} is the angle between the plane defined by the normal n and the ray defined by the direction v_c. Therefore,

$$\delta\|x_w\|_2 = \|\delta\alpha\|\|v_e\|_2 = \left|\frac{n_1}{\|n\|_2 \sin\Theta_{nv}}\right| |\delta x_p|. \tag{23}$$

[0241] The ratio

$$\cos\theta_P = \frac{n_1}{\|n\|_2}$$

has a geometrical interpretation of cosine of the projection angle; substituting it into Eq. (23) yields the sensitivity of the reconstructed object point to perturbations in the stripe id:

$$\frac{\delta\|x_w\|_2}{\|\delta x_p\|} = \left|\frac{\cos\theta_P}{\sin\Theta_{nv}}\right|. \tag{24}$$

[0242] Calibration

[0243] In this section we assume that the forward projection operator T is unknown and has to be estimated from a given set of measured $\{(x_c, x_p)_n\}_{n=1}^{N}$ and corresponding known $\{x_w\}_{n=1}^{N}$. Explicitly, it is desired to find such C_c and C_p that obey

$$(x_c)_k = C_c (x_w)_k \tag{25}$$

$$(x_p)_k = C_p (x_w)_k, \tag{26}$$

for k=1, . . . , N. Since data measurement is not perfect (e.g., both the camera and the projector resolution is finite), no projection operator will fit the data perfectly. Therefore, it is necessary to find such a T^{-1} that will relate the measured and the known data in an optimal way. It is thus important to address the optimality criterion.

[0244] Mclvor and Valkenburg (see above) study the possibility of optimizing separately the camera and the projector forward projections in the sense of the L_2 norm. Mathematically, this can be formulated as

$$C_c = \text{argmin}\sum_{k=1}^{N} \|C_c(x_w)_k - (x_c)_k\|_2^2 \quad \text{s.t.} \quad C_c \in PPM \tag{27}$$
$$C_p = \text{argmin}\sum_{k=1}^{N} \|C_p(x_w)_k - (x_p)_k\|_2^2 \quad \text{s.t.} \quad C_p \in PPM.$$

[0245] Let us define

$$B_k = \begin{bmatrix} (x_w)_k & 0 \\ 0 & (x_w)_k \\ -(x_c)_k(x_w)_k & -(y_c)_k(x_w)_k \end{bmatrix}^T \tag{28}$$
$$l = [c_1, c_2, c_3]^T,$$

where c_k is the k-th row of C_c. Using this notation, the set of N equations (25) can be rewritten as

$$B_k l = 0, \tag{29}$$

for k=1, . . . , N, which in turn can be expressed as a single homogenous linear equation

$$Al = 0, \tag{30}$$

where $A = [B_1^T, \ldots, B_N^T]^T$. The vector of variables l is the camera projection matrix Cc needed to be determined. Since the camera PPM is defined up to a scaling factor, we will demand $\|l\|_2 = 1$ in order to avoid the trivial solution. With physically measured data, the matrix A will usually have full rank and therefore, no l will be an exact solution of eq. (30). However, one can find the best least-squares solution by solving

$$l = \text{argmin}\|Al\|_2^2 \text{ s.t. } \|l\|_2 = 1, \tag{31}$$

and ensuring that the obtained C_c is a valid PPM. Solving eq. (31) is equivalent to solving eq. (27) for the camera matrix, and its solution minimizes the square error between the measured image plane coordinates of the set of fiducial points and those obtained by projecting the set of the corresponding points in WCS onto the camera image plane.

[0246] Similarly, replacing B_k and l in eq. (28) with

$$A = [B_1^T, \ldots, B_N^T]^T \quad B_k = \begin{bmatrix} (x_w)_k \\ -(x_p)_k(x_w)_k \end{bmatrix}^T \tag{32}$$
$$l = [p_1, p_2]^T$$

yields the L_2 minimization problem, eq. (27), for the projector matrix.

[0247] The optimization problem of eq. (31) is a minimum eigenvalue problem and it can be shown that l minimizing $\|Al\|_2$ is the eigenvector corresponding to the minimum eigenvalue of A^TA. It must be noted, however, that since usually the minimum eigenvalue of A^TA is very small, numerical inaccuracies are liable to rise.

[0248] Solution to the problem 27 finds two PPMs that minimize the squared error between the measured data and the forward projection of the known fiducial points in WCS into the camera and the plane coordinate systems. However, what is actually needed is to minimize the squared error between the known fiducial points in WCS and the backward-projected measurements. Mathematically, this can be formulated as

$$T = \text{argmin}\sum_{k=1}^{N} \|T^{-1}(x_c, x_p)_k - (x_w)_k\|_2^2 \tag{33}$$
$$\text{s.t. } C_c, C_p \in \text{text } PPM$$

[0249] The above problem is no more separable and is non-convex; therefore, it has to be solved by numerical global optimization methods. Still, an efficient solution in a few iterations is possible using the Newton method, since the number of variables in the problem is small (3×4+2×4=20) and both the cost function, its gradient, and the Hessian can be computed analytically. As the starting point for iterative optimization, a solution of eq. (27) can be used.

[0250] Since the calibration process is performed only once, additional computational complexity can be used in order to obtain better projection estimation and better reconstruction results.

[0251] FIG. **5** shows the sensitivity of the reconstructed object point to perturbations in x_p; the smaller the angle θ_p, the larger the error $\delta\|x_w\|_2$.

[0252] Implementation of Reconstruction

[0253] In our implementation, we used temporal encoding, which allowed to obtain a dense z-map of the scanned objects. Eight binary patterns, encoding the stripe id using the Gray code were projected onto the object and 8 corresponding images I_k were acquired (I_1 corresponding to the most significant bit). In addition, we acquired a full-darkness image I_L (the projector's LCD was blackened) and a full-illumination image I_H (the projector's LCD was set to maximum intensity). These two images served for compensation of ambient light and the non-constant albedo of the object.

[0254] The quantity $I_k(x, y)$ reflects the illumination of the object in pixel (x, y) at darkness and differs from zero only due to presence of ambient illumination. Since the reflectance of objects at illumination levels used in normal conditions obeys linear superposition law, subtracting I_L from the rest of the images compensates for the ambience light. The quantity $I_H(x, y)-I_L(x, y)$ is proportional to the object albedo at the pixel (x, y).

[0255] We define a set of 8 normalized intensity images

$$J_k(x, y) = \frac{I_k(x, y) - I_L(x, y)}{I_H(x, y) - I_L(x, y)}. \tag{34}$$

[0256] A normalized intensity image $J_k(x, y)$ has the values in the range [0, 1] and reflects the amount of light irradiated onto the object surface at pixel (x, y). The value of 1 stands for full illumination, whereas the value of 0 stands for no illumination. Theoretically, J_k should be binary images: 1 where a light stripe is present and 0 in places where there is a dark stripe. In practice, however, J_k are not binary and we therefore define

$$B_k(x, y) = \begin{cases} 1: & J_k(x, y) > 0.5 \\ 0: & J_k(x, y) \le 0.5 \end{cases}. \tag{35}$$

[0257] Better results were obtained when $J_k(x, y)$ was smoothed with a Gaussian filter prior to binarization. FIG. **6**A-D depicts I_H (FIG. **6**A) and I_L (FIG. **6**B) as well as the LSB (FIG. **6**D) pattern and the MSB (FIG. **6**C) pattern.

[0258] FIG. **7**A-E presents the normalized intensity image $J_3(x, y)$, the corresponding binary image $B_3(x, y)$ and a profile of a vertical line from these two images. FIG. **7**A shows the raw image corresponding to one embodiment of a stripe pattern, FIG. **7**B shows the normalized intensity image for that stripe pattern, FIG. **7**C shows the binary image for that stripe pattern and FIG. **7**D shows the fidelity image for that stripe pattern. All images are normalized. FIG. **7**E shows the profile of a vertical line from the normalized intensity image (FIG. **7**B) (dashed line) and the binary image (solid vertical lines).

[0259] For every pixel (x, y), we define the stripe code as the Gray code sequence

$$S(x,y)=[B_1(x,y), \ldots, B_8(x,y)]. \tag{36}$$

[0260] Decoding S(x, y) yields a number T(x, y)Σ[0, 1], which will be referred to as stripe id. Note that T(x, y) is not really continuous but rather has the values T(x, y)Σ$\{2^{-N}$n: n=0, . . . , $2^N-1\}$ (in the example, N=8).

[0261] For every pixel, $x_p(x, y)=T(x, y)$ defines the projector coordinate of an unknown object point corresponding to the pixel (x, y), transformed by the projector PPM. Similarly, the pixel indices (x, y) define the camera image plane coordinates $x_c=x$, $y_c=y$ of the object point projected onto the camera coordinate system. Given the camera and the projector PPMs, world coordinates of the object point can be calculated according to eq. (21).

[0262] Pixel Fidelity Estimation

[0263] It is obvious that although both $J_k(x, y)=0.95$ and $J_k(x, y)=0.55$ will be binarized as $B_k(x, y)=1$, they should definitely be treated differently. In the first case, one may say that the pixel (x, y) in image k is indeed illuminated with high probability, whereas in the second case the probability of that pixel to be non-illuminated is almost equal to the probability of it being illuminated.

[0264] In order to give a quantitative measure of the pixel fidelity, let us assume that the measured normalized intensity image $J_k(x, y)$ is obtained from some ideal binary image $B_k^0(x, y)$ contaminated by zero-mean Gaussian noise $\xi(x, y)$ with variance σ^2. In case $J_k(x, y)>0.5$, the pixel fidelity can be defined as

$$F_k(x, y) = P\{J_k(x, y) + \xi(x, y) > 0.5\} = \Phi\left(\frac{0.5 - J_k(x, y)}{\sigma}\right),$$

where Φ denotes the c.d.f. of the normal distribution. The lower value of F_k is 0.5 and it is obtained when $J_k(x, y)=0.5$. Similarly, for $J_k(x, y)<0.5$, the fidelity is

$$\begin{aligned} F_k(x, y) &= P\{J_k(x, y) + \xi(x, y) < 0.5\} \\ &= 1 - \Phi\left(\frac{0.5 - J_k(x, y)}{\sigma}\right) \\ &= \Phi\left(\frac{J_k(x, y) - 0.5}{\sigma}\right). \end{aligned}$$

[0265] Binarization errors in images corresponding to the most significant bit of the stripe code affect more the resulting stripe id T than errors in the least significant bit. Therefore, pixel fidelity in each stripe should be weighted by the stripe significance. We define the pixel fidelity as the weighted sum of the pixel fidelities in all stripes

$$F(x, y) = \sum_{k=1}^{N} w_k P_k(x, y) = \sum_{k=1}^{N} w_k \Phi\left(\left|\frac{0.5 - J_k(x, y)}{\sigma}\right|\right),$$

where $w_k=2^{-k}$ is the significance of stripe k, and N is 8 in our implementation. The variance σ^2 was set empirically to 1. FIG. **8**A-B shows the decoded stripe code T (FIG. **8**A) of a scanned object and the fidelity image F (FIG. **8**B).

[0266] Pixel fidelity can also provide important information and can be used, for example, for weighted mesh smoothing or decimation. For example, the pixel fidelity map can be used to obtain sub-stripe resolution, as shown below.

[0267] Sub-Stripe Resolution

[0268] One of important concerns in structured light systems is sub-stripe resolution. The stripe code T, which usually has granular nature due to quantization can be approximated by a continuous smooth surface, taking into account the fidelity map. We used a separable cubic spline, which was fitted to the image T with weighting inverse proportional to pixel fidelity. As the result, a smooth stripe id image $\tilde{T}$ with sub-stripe resolution was obtained.

[0269] Let us denote by Bv and Bu the orthonormal spline bases corresponding to the rows and the columns of T, respectively. Decomposition of the T in the two-dimensional separable basis obtained as the tensor product of Bv and Bu can be expressed as

$$C=B_u{}^T T B_v, \tag{37}$$

or, alternatively, as

$$c=B^T t, \tag{38}$$

where t is the column-stack representation of T, c is a vector of spline coefficients and $B=B_n \otimes B_u$ is the Kronecker product of the row and the column bases. Weighted spline fitting constitutes to finding such spline coefficients c that minimize

$$\sum_k \frac{1}{f_k}((Bc)_k - t_k)^2, \tag{39}$$

where f_k denotes the fidelity of the pixel t_k. We also add a controllable penalty on irregularity of the smoothed image $\tilde{t}$=Bc. In matrix notation, the weighted spline fitting problem reads

$$c=\operatorname{argmin}\{\|WBc-Wt\|_2{}^2+\lambda\|DBc\|_2{}^2\}, \tag{40}$$

where

$$W=\operatorname{diag}\left\{\frac{1}{f_k}\right\}$$

is the weighting matrix, D is the matrix defining the irregularity penalty and λ is the smoothness parameter, controlling the tradeoff between smoothness of $\tilde{t}$ and faith to the original data.

[0270] The analytic solution for eq. (40) is

$$c=[B^T B+\lambda(DB)^T(DB)]^\dagger t, \tag{41}$$

where $A^\dagger=(A^T D)^{-1}A$ denotes the Moore-Penrose pseudoinverse.

[0271] Since different amount of smoothing should be usually applied in the horizontal and the vertical directions of T, it is reasonable to use two penalty factors with two separate smoothness parameters, which control the smoothness in each direction. We used the L_2 norm of a finite difference operator as the penalty factor, yielding

$$c=[B^T B+\lambda_x(D_X B)^T(D_x B)+\lambda_y(D_y B)^T(D_y B)]^\dagger t, \tag{42}$$

where D_x and D_y are the row-wise and the column-wise discrete derivative operators and λ_x and λ_y are smoothness parameters controlling the smoothness of $\tilde{T}$ in the x- and y-direction, respectively. The resulting smooth stripe id image $\tilde{T}$ is given (in column stack representation) by $\tilde{\bar{t}}$=Bc.

[0272] FIG. **9**A-B presents the T image of a human face obtained by directly decoding the stripe ids (FIG. **9**A) and by using fidelity-weighted smooth cubic spline fitting (FIG. **9**B). Note that quantization noise is less significant in the latter case.

[0273] FIG. **10**A-C depicts the reconstructed surface with (FIG. **10**B) and without (FIG. **10**A) using sub-stripe resolution. FIG. **10**C shows a vertical profile of the Z-map without using sub-stripe resolution (solid) and using sub-stripe resolution (dashed).

[0274] Calibration

[0275] In an embodiment, to find the camera and the projector matrices, the automatic calibration procedure described hereinabove was used. As the calibration object, a precisely built 15×15×15 cm wooden pyramid attached with 3 mutually perpendicular planes attached to a "background" plane, was used. Object surfaces were made nearly Lambertian using white mate finishing.

[0276] 228 circular fiducial points were marked on the calibration object surfaces. The points were grouped into sets of collinear equally-spaced marks, 3 sets of 33 points each on the background plane, and two sets of 22 points each on each of the pyramid sides (FIG. **11**). WCS was defined as the local coordinate system of the calibration object.

[0277] At the first stage, the calibration object was scanned and a sub-stripe resolution stripe id image $\tilde{T}$ was calculated from the raw data. At the second stage, the full-illumination image I_H was binarized, the fiducial points were automatically located and their centroid coordinates were calculated. A set of 228 stripe ids at locations corresponding to the fiducial point centroids, together with the centroid locations themselves was used as the input for the calibration algorithm. For numerical stability, WCS coordinates of the calibration objects, the image plane coordinates of the camera and the projector stripe ids were normalized to [−1, 1].

[0278] First, camera and projector PPMs that minimize the forward projection error were found by solving eq. (31). These matrices were used as the initial point of the Newton algorithm, which converged to the solution of eq. (33), yielding camera and projector matrices, which minimize the back-projection error. FIG. **12**A-B depicts the forward projection of the theoretically calculated calibration object fiducial points, onto the camera and the projector coordinate system. The measured fiducial points centroids and projector stripe ids are shown as a reference. FIG. **12**A shows the object points reprojected to the camera image plane (circles) and the measured fiducial point centroids (crosses). FIG. **12**B shows the object points reprojected to the projector coordinate system (dashed) and the measured stripe ids (black). In both FIG. **12**A and FIG. **12**B, the coordinates are normalized.

[0279] Table 1 shows the RMS and the maximum reconstruction errors of the calibration object in five tests with random camera and projector locations. Two cases are studied: 1) when the camera and the projector matrices are obtained by minimizing the forward projection error and 2) when the camera and the projector matrices are obtained by minimizing the backward projection error. The errors were calculated on a set of 100,000 points, with the analytical plane equations of the calibration object serving as a reference. Table 2 shows the improvement of the RMS and the maximum reconstruction error when using the optimal backprojection instead of the optimal forward projection. RMS was improved in all tests (improvement ranging from 1.44% to 45.66%, 12% on average). Maximum error was improved in all tests except Test 2, where the maximum error obtained using the optimal backprojection worsened by 6.58% (the fact that improvement in the RMS error was observed in Test 2 suggests that the degradation in the maximum error might have been caused by a spurious pixel). The maximum improvement, about 50%, was obtained in Test 5.

TABLE 1

RMS and maximum errors for reconstruction of the calibration object using the optimal forward projection and the optimal backward projection.

	Optimal projection		Optimal backprojection	
Test	RMS (mm)	Max. (mm)	RMS (mm)	Max. (mm)
1	0.0624	0.2790	0.0577	0.2295
2	0.0626	0.2881	0.0616	0.3084
3	0.0423	0.2054	0.0417	0.1723
4	0.1599	0.6823	0.1556	0.6337
5	0.1579	0.6170	0.1084	0.4122

TABLE 2

Improvement in the RMS and the maximum error in reconstruction of the calibration object when using the optimal backprojection instead of the optimal forward projection.

Test	RMS	Max.
1	8.15%	21.57%
2	1.62%	−6.58%
3	1.44%	19.21%
4	2.76%	7.67%
5	45.66%	49.68%

[0280] The RMS error was about 0.5 mm in Tests 1-3 and about 1.6 mm in Tests 4-5. The latter degradation of the reconstruction quality was due to the highly oblique position of the calibration object with respect to the camera, which resulted in lower SNR, since less light was reflected from the object planes.

[0281] FIG. **13**A-D shows two profiles of the reconstructed calibration object. Analytical object profiles are shown as a reference. FIG. **13**A shows the reconstructed profile along the solid line in FIG. **13**B, while FIG. **13**C shows the reconstructed profile along the solid line in FIG. **13**D. In FIGS. **13**A and **13**C, the solid line shows the reconstruction using the optimal forward projection and the dash-dotted line shows the reconstruction using the optimal backprojection. The dashed line shows the real profile. All units are in cm.

[0282] FIG. **14** illustrates an embodiment of the system (**1100**). In this embodiment, the system comprises a PC (**1140**) controlling a camera unit (**1115**) and modulation unit (**1135**) for spatial and temporal modulation of the light source, a light source (**1130**), a camera (**1110**) and an endoscope (**1110**).

[0283] The camera unit (**1115**) controls the imaging system, including, where necessary, focusing of the camera (**1110**) and, where necessary, manipulation of the system optics so that the desired portion of the scene is at the center of the field of view. Images are transmitted from the camera (**1110**) to the PC (**1140**) via the camera unit (**1115**).

[0284] The modulation unit (**1135**) controls positioning of the light (**1132**), both spatially and temporally, in order to provide a set of structured light rays as described hereinabove. The modulation unit (**1135**) can be "upstream" of the light source (**1130**), as shown, or "downstream" of the light source (**1130**).

[0285] In embodiments where the modulation unit (**1135**) is "upstream" of the light source (**1130**), the modulation unit (**1135**) controls the light source (**1130**) directly so that light (**1132**) is emitted from different positions in the source (**1130**) at different times, in order to provide the desired set of structured light rays.

[0286] In preferred embodiments, where the modulation unit is "downstream" of the light source (**1130**), the modulation unit (**1135**) controls positioning of the light beam (**1132**); light from the light source (**1130**) is maneuvered by the modulation unit (**1135**) to provide the desired set of structured light rays.

[0287] Software to carry out the functions of the modulation unit (**1135**) and the camera unit (**1115**) can be local, within the unit, or central, within the PC (**1140**).

[0288] The structured light rays are then transmitted through the endoscope (**1120**) so as to illuminate the region of interest.

[0289] Reflected radiation from the objects in the region of interest is transmitted back through the endoscope (**1120**) so as to be received by the camera (**1110**), and the camera image is transmitted via the camera unit (**1115**) to the PC, where the 3D image of the region of interest is reconstructed, as described hereinabove. Manipulation of the camera image, such as elimination of background light or binarizing, as described hereinabove, can be carried out in the camera unit (**1115**), in the PC (**1140**), or any combination thereof.

[0290] FIG. **15** shows an embodiment of a distal end (**1000**) of the endoscope. Modulated light (**1132**), after transmission through the endoscope, is emitted by the endoscope's optical transmission channels. After reflection from an object (not shown) it is received by the distal end of the camera optics (**1020**). The distal end of the camera optics comprises an optical element (**1025**), typically a lens or prism. This optical element (**1025**) is at an angle to the laparoscope other than 90 degrees, since, as described hereinabove, the optic axis of the camera can not be parallel to the plane of the structured light. In preferred embodiments, the angle between the plane of the structured light rays and the normal to the face of the distal optical element is between about 30 degrees and about 60 degrees.

Example 2

[0291] In another embodiment, the physical setup is similar to that of the embodiment of Example 1 (see FIG. **1**) and, as in the embodiment of Example 1, a calibration object of known shape and size (the world object) is illuminated by a set of rays of light (the projector, in the projector coordinate system) emitted from known positions, in known directions and at known times. These rays are reflected from the calibration object (the object, in the world coordinate system) and generate at least one 2D camera image (the camera image, in the camera coordinate system).

[0292] However, instead of the operators of Example 1, polynomial fits are made to the known spot positions on the camera images, given the known ray positions, the known spot positions on the camera images and the known shape and size of the calibration object. From the polynomial fits, the locations of positions on the surface of an unknown object can be found.

[0293] In the embodiment of Example 2, the projector (light source) projects a coded stripe pattern on the object or objects to be viewed and the camera captures an image of the reflected light. Hence, for each visible point in the scene there is a corresponding stripe number and image location (in pixel coordinates). Given the parameters of the system, each strip value defines a plane in the world (the space being viewed) and each pixel defines a ray in the world. The intersection of the plane and the ray defines a unique 3D location in the world. The parameters of the system are obtained during calibration. As in Example 1, a calibration object is placed at a known position in the field of view. The calibration object comprises a set of fiducial marks whose spatial location is known to high accuracy. The system is operated normally and the pixel coordinates are found for each of the fiducial marks. These triples of fiducial mark, pixel and stripe coordinates are used to estimate the unknown parameters of a mathematical model of the system.

[0294] In practice, the projector projects a sequence of 9 banded light patterns onto the scene. The first pattern is full illumination. The remaining patterns provide temporal encoding, with each of the 8 patterns providing one bit in an 8 bit binary grey code for the stripe value. In general, for a b bit code, the k^{th} bit (where k=0, 1, . . . , b−1) of the code for the n_{th} value (n=0, 1, . . . , 2^{b-1}) is given by

$$\left[\frac{1}{2}\left(\frac{n}{2^k}+1\right)\right] \bmod 2.$$

An important property of the code is that no two edges (level changes) are coincident throughout the sequence. As the most likely place to erroneously read a bit is at a level change, the code helps reduce the possibility of detecting more than one bit of the code erroneously. In addition, detecting a bit incorrectly at a level change only alters the stripe value by one. It should be noted that this stripe encoding completely eliminates the need for resolving any correspondence between points in the image and stripes.

[0295] Projector lens distortion results in each stripe forming a slightly curved surface instead of a plane, and camera lens distortion results in the image point being slightly displaced from its nominal position. Furthermore, the discrete nature of pixel-based cameras and projectors gives rise to uncertainty in the true pixel coordinates and stripe value.

[0296] In preferred variants of the present embodiment, correcting for the effects of projector lens distortion is included in the model of the projector.

[0297] In preferred variants of the present embodiment, correcting for the effects of camera lens distortion is via subpixel and substripe operators.

[0298] In the present embodiment, the uncorrected transformation of a point P from the world coordinate system C_w to the camera coordinate system C_c is

$$\begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} = R_c \begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix} + T_c \tag{43}$$

where $X_c=(x_c, y_c, z_c)$ is the location of the point in camera coordinates, $X_w=(x_w, y_w, z_w)$ is the location of the point in camera coordinates, R_c is a 3×3 rotation matrix and T_c is a 3×1 translation vector.

[0299] The "principal point" is the intersection of the imaging plane with the optical axis. Without loss of generality, a 2D image coordinate system can be defined as being in the image plane with its origin located at the principal point. Let p be the projection of the point P onto the image plane for a non-distorting projector and let the coordinates of p be ($\tilde{x}_i$,$\tilde{y}_i$, 0). Then

$$\begin{pmatrix} \tilde{x}_i \\ \tilde{y}_i \end{pmatrix} = \frac{f_c}{z_c}\begin{pmatrix} x_w \\ y_c \end{pmatrix} \tag{44}$$

where f_c is the "principal distance".

[0300] As described above, the projective lenses slightly distort the plane of the projected light into a curved surface. To correct for this, let (x_i, y_i, 0) be the observed location in the image plane of the point p, after projection by a real, distorting projection system. Then,

$$\begin{pmatrix} x_i \\ y_i \end{pmatrix} = \begin{pmatrix} \tilde{x}_i \\ \tilde{y}_i \end{pmatrix}[1 + K_c(\tilde{x}_i^2 + \tilde{y}_i^2)] \tag{45}$$

where K_c is a coefficient determined by the amount of radial distortion.

[0301] The effects of pixels size and imager speed can also be factored in. Let C_{pixel} be a pixel coordinate system associated with the digital image, where the location of a point is given by (x,y). Then the pixel coordinates are related to the image coordinates by

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} s_c^x & k_c \\ 0 & s_c^y \end{pmatrix}\begin{pmatrix} x_i \\ y_i \end{pmatrix} + \begin{pmatrix} c_c^x \\ c_c^y \end{pmatrix} \tag{46}$$

where s_c^x and s_c^y are scale factors in pixels/mm, c_c^x and c_c^y are the pixel coordinates of the principal point and k is a shear coefficient in pixel/mm.

[0302] The model for the projector is similar to that for the camera, as the projector can be regarded as a camera with a 1D image, acting in reverse.

[0303] However, the projector model differs from the camera model in that the stripe coordinate system C_s is 1D, unlike the 2D camera coordinate system C_p, leading to the equation:

$$x_z=s_p^x x_i+c_p^x \tag{47}$$

where s_p^x is a scale factor and c_p^x is the pixel coordinate of the principal point of the projection system.

[0304] Physically, each stripe value x_x gives rise to a unique line on the projector given by $\{(x_i,y_i):x_i=(x_s-c_p^x)/s_p^x, y_i \in \Re\}$. The line is projected and distorted by the lens, giving rise to a slightly curved surface in the world.

[0305] Altogether, the following set of equations describes the transformations:

$$\begin{pmatrix} x_c \\ y_c \\ z_c \end{pmatrix} = R_c \begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix} + T_c \tag{43}$$

$$\begin{pmatrix} \tilde{x}_i \\ \tilde{y}_i \end{pmatrix} = \frac{f_c}{z_c} \begin{pmatrix} x_w \\ y_c \end{pmatrix} \tag{44}$$

$$\begin{pmatrix} x_i \\ y_i \end{pmatrix} = \begin{pmatrix} \tilde{x}_i \\ \tilde{y}_i \end{pmatrix} [1 + K_c(\tilde{x}_i^2 + \tilde{y}_i^2)] \tag{45}$$

$$x_s = s_p^N x_i + c_p^x \tag{47}$$

[0306] The above models describe the geometric behavior of the camera and projector and are based on a physical understanding of these devices. $K_c=0$ and $k_c=0$ describe a perfect camera. Similarly, $K_p=0$ describes a perfect projector.

[0307] It is clear that there is a redundant parameter within the set of camera parameters $\{s_c^x, s_c^y, f_c\}$. This can be dealt with by arbitrarily fixing one of them. For the calibrations described hereinbelow, f_c is set to 1.

[0308] Lens distortion has been incorporated as a function of the transform from $(\tilde{x}_i, \tilde{y}_i, 0)$ to $(x_i, y_i, 0)$. This is because the distortion is a 2D phenomenon whereas only one coordinate of the position of a point on the projector emitter is available. However, the ranges of both formulations are almost equivalent for typical system configurations. Therefore, this modification makes little difference to the solution.

[0309] The camera and projector models can be summarized as follows. Let

$$\Theta_x(s_c^x s_c^y c_c^x c_c^y k_c K_c \omega_c^1 \omega_c^2 \omega_c^3 T_c^1 T_c^2 T_c^3)^t \tag{48}$$

$$\Theta_p(s_p^x c_p^x K_p \omega_p^1 \omega_p^2 \omega_p^3 T_p^1 T_p^2 T_p^3)^t \tag{49}$$

where ω_c^k, k=1 . . . 3 and ω_w^k, k=1 . . . 3 parameterize R_c and R_p respectively (e.g. Euler angles). The first six parameters of the camera model and the first three parameters of the projector model are referred to as "intrinsic parameters" because they are independent of the world coordinate frame.

[0310] Using the above, the transformation from world coordinates p_w to pixel coordinates p_p can be written as

$$p_p = F_c(p_w; \Theta_c). \tag{50}$$

[0311] Similarly, the transformation from world coordinates to the stripe value p_x can be written as

$$p_s = F_p(p_w; \Theta_p). \tag{51}$$

[0312] Both the calibration and spatial intersection procedures require the pixel coordinates and the stripe value of points of interest in the world (field of view). Obtaining good estimates for the value of these quantities is important in order to obtain accurate estimates of the parameters of the system during calibration and accurate estimates of 3D point locations during spatial intersection.

[0313] Subpixel Estimation

[0314] During calibration, the subpixel locations of the centroids of the fiducial marks on the calibration reference are required. The grayscale centroid operator can be used to estimate the centroids of the fiducial marks in the image. Such centroid-based techniques have the following advantages:

[0315] a. They are robust to noise, since they are based on integration rather than the differentiation of many edge detectors.

[0316] b. They are robust to small amounts of aliasing. Theoretically, they are exact if the sampling frequency is greater than the Nyquist frequency.

[0317] c. They are computationally inexpensive.

[0318] However, the centroid of the image of a fiducial mark does not in general coincide with the image of the centroid, due to perspective distortion. This introduces a systematic error in the centroid estimate and is a fundamental limitation of centroiding techniques.

[0319] Ignoring lens distortion, an estimate of this error can be obtained as follows. Consider a flat circular region Δ of radius r. let n be the normal to Δ and q be the location of the centroid of Δ, both in camera coordinates. If c denotes the image of the centroid and ĉ denotes the centroid of the image of Δ then

$$c = \frac{f_c}{t_3} \begin{pmatrix} t_1 \\ t_2 \end{pmatrix} \tag{52}$$

$$\hat{c} = \frac{f_c}{t_3^2 + r^2(n_3^2 - 1)} \begin{pmatrix} t_1 t_3 + r^2 n_1 n_3 \\ t_2 t_3 + r^2 n_2 n_3 \end{pmatrix}. \tag{53}$$

[0320] As required, ĉ reduces to c when $n=e_3$ (Δ parallel to the image plane. The error in the image plane is given by $e_p=c-\hat{c}$. This error can be transformed into pixel coordinates using the scale factors and shear coefficient defined hereinabove (eq. 46).

[0321] FIG. **16** shows a plot of these errors in pixel coordinates for a typical calibration configuration. Each error is represented as a vector with its base at the associated fiducial mark. The vector magnitudes have been scaled by a factor of 1000 for clarity. In the current system, these errors are considered acceptable.

[0322] During special intersection, two situations can arise, one where the image location is freely chosen and the other where it is dictated by a feature in the world. The need to use subpixel estimation does not arise in the first situation, e.g., during generation of a dense range map with image locations at the pixel lattice points. The type of subpixel operator used during the second situation depends on the nature of features (such as, but not limited to edges, ridges, blobs, voids, or transparent or translucent regions).

[0323] Substripe Estimation

[0324] During calibration and special intersection, the substripe values of specified world points are required.

[0325] Substripe estimation is more difficult than subpixel estimation. One reason for this is that the stripe information is not directly available from the projector in the sense that the pixel location information is available from the camera. It is the images of the stripes cast on the scene which are used to recover the stripe values. In this way, the stripes are effectively samples twice, once by the predetermined locations of the stripes emitted by the projector, and once from the image in the camera. Another difficulty, specific to temporally encoded systems, is that the stripe values are encoded in a sequence of images rather than available in a single image as for pixel locations.

[0326] It is assumed that the 8 bit stripe value is available for each pixel in the image. The image formed from these values is referred to as a "stripe image". The discrete nature and coaresse quantization of the stripe image gives rise to poor accuracy if used directly. The algorithm adopted for substripe estimation is simple. A region of interest, Ω, is established with its center at the subpixel location, (x_p,y_p), where the substripe estimate, x_x, is to be determined. A least-squares polynomial facet is fitted to the stripe image in Ω and the substripe estimate made by interpolating this facet.

[0327] If the underlying surface is flat, a planar facet is fitted to the stripe image Ω. Assuming no lens distortion in the camera and the projector, the stripe values and the pixel coordinates for a planar patch in the world will be related by a rational function because the composition of two projective maps is a projective map. Hence a planar facet does not model perspective effects precisely. The errors introduced by using a planar facet can be estimated as follows.

[0328] Let C_c and C_p denote the 3×4 and 2×4 Perspective Transformation Matrices (PTMs) for the camera and projector, respectively. Both the camera and the projector are assumed to be distortionless. Let T be a 4×3 homogeneous transformation matrix describing the coordinate transformation between a 2D coordinate system associated with the planar patch and the world coordinate system. It follows that

$$a\begin{pmatrix} x_s \\ 1 \end{pmatrix} = C_p T (C_c T)^1 \begin{pmatrix} x_p \\ y_p \\ 1 \end{pmatrix} \tag{54}$$

[0329] This shows that the stripe values and pixel coordinates are related by an equation of the form

$$x_s = \frac{n_1 x_p + n_2 y_p + n_3}{d_1 x_p + d_2 y_p + d_3} \tag{55}$$

[0330] Let x_x be the true substripe value at subpixel location (x_p,y_p) calculated using eq. (54). Let (X_p, Y_p) be the n×2 matrix of pixel coordinates in Ω and X_x be the n vector of substripe values at coordinates (X_p,Y_p). The 3×1 vector of coefficients of the least squares plane fitted to X_x on Ω is given by

$$c=(A^tA)^{-1}A^tX_s \tag{56}$$

where $A=[X_p\ Y_p\ 1_n]$ is the n×3 design matrix associated with the plane. The estimate of the x_x is given by

$$\hat{x}_s=c_x x_p+c_2 y_p+c_3 \tag{57}$$

and the error is given by $c_{\hat{x}s}=x_s-\hat{x}_s$.

[0331] FIG. **17** shows a stem plot of these errors for a typical calibration configuration. The horizontal axis gives the stripe value calculated at the centroids of the fiducial marks and the vertical lines give the error in stripes at these locations. The errors are insignificant compared with the effects which result from the 8 bit quantization of the stripe value and therefore can typically be ignored.

[0332] In the more general case of a curved surface, higher order 2D polynomial facets are fitted to the stripe image. The order of the facet model depends on the size of the region of interest Ω, which must cover a sufficient number of stripes. Typically, a region of interest of size 17×17 pixels and 2D third-order polynomials are used. Note that polynomial fitting does not introduce blurring in the sense of low-pass filtering. For example a polynomial of degree n (which can have considerable oscillation) is invariant to a polynomial filter of order n (i.e. the filter which is defined by fitting and interpolating a polynomial of degree n).

[0333] Planar facets are only used when the surface under consideration is known to be flat, such as the faces of the calibration reference. In all other cases. a polynomial facet is used. The planar facet is embodied because it provides superior estimation when the surface has very low curvature.

[0334] Calibration

[0335] Calibration involves estimating the unknown parameters relating the world points, the projector points and the image points from a number of known world points and their corresponding pixel coordinates and stripe values.

[0336] For a calibration object with n fiducial marks, let $p_w(j)$, $p_p(j)$ and $p_s(j)$ be the world coordinates, the pixel coordinates and the stripe coordinates, respectively, of the jth fiducial mark. In addition, let P_w, P_p and P_s be vectors of sizes 3n, 2n and n, respectively, formed by stacking the coordinate vectors for the world points, the pixel points and the stripe points, respectively. The vectors P_p and P_s are measured from the image sequence as described hereinabove and will consequently suffer from measurement noise.

[0337] If μ_{P_p} and μ_{P_s} are the true values of P_p and P_s, respectively, then the observations are given by

$$P_p=\mu_{P_p}+\epsilon_p \tag{58}$$

$$P_s=\mu_{P_s}+\epsilon_s \tag{59}$$

and the model can be written as

$$\mu_{P_p}-F_c(P_w;\Theta_c)=0 \tag{60}$$

$$\mu_{P_s}-F_p(P_w;\Theta_p)=0 \tag{61}$$

[0338] In this derivation, the assumptions are:

[0339] P_w is measured without error.

[0340] $P_p \sim N(\mu_{P_p}, \sigma_p^2 I_{2n})$

[0341] $P_s \sim N(\mu_{P_c}, \sigma_s^2 I_n)$

[0342] Maximum Likelihood Estimation of $\{\Theta_c, \Theta_p\}$ leads to the non-linear least squares (NLLS) problem

$$\min_{\Theta_c} \|P_p - P_c(P_w; \Theta_c)\|^2 \tag{62}$$

$$\min_{\Theta_p} \|P_s - P_p(P_w; \Theta_p)\|^2 \tag{63}$$

which can be solved using any general NLLS solving algorithm known in the art. Non-limiting examples of such algorithms are Gauss-Newton or Levenberg-Marquardt.

[0343] Obtaining good initial estimates for the parameters is desirable as (1) it helps ensure that the global minimum is obtained and (2) reduces computation by reducing the number of iterations required. Initial estimates can be obtained from a variety of sources, depending on the nature of the problem. A typical approach is to estimate and decompose the PTMs for the camera and the projector.

[0344] Spatial Intersection

[0345] Special intersection is used to find an estimate of the location of a point in the world coordinate system given its pixel coordinates and stripe value. The lens distortion in the projector results in slightly curved surfaces being projected onto the scene rather than planes. Consequently, the special intersection procedure involves solving a homogeneous non-linear system in three variables. However, linear methods can be used to calculate a good initial approximation and physical considerations preclude the presence of any other solutions in a large neighborhood of the true solution.

[0346] Let $p_p=(x_p,y_p)^t$ and $p_x=(x_s)$ be the pixel coordinates and stripe value of a point P. Then the world coordinates of P, denoted p_W, are given by the solution of the non-linear system

$$\begin{pmatrix} p_p \\ p_s \end{pmatrix} - \begin{pmatrix} F_c(p_w\colon \Theta_c) \\ F_p(p_w\colon \Theta_p) \end{pmatrix} = 0 \tag{64}$$

[0347] This problem can be solved using any general technique known in the art, for non-limiting example, a quasi-Newton strategy.

[0348] The initial linear estimate of p_w is found as follows. Let C_c^k be the kth row of the 3×4 camera PTM and C_p^k be the kth row of the 2×4 projector PTM. Then the PTM equations relating p_w,p_p and p_x, i.e.,

$$\beta_p\begin{pmatrix} p_p \\ 1 \end{pmatrix} = C_c\begin{pmatrix} p_w \\ 1 \end{pmatrix} \beta_s\begin{pmatrix} p_s \\ 1 \end{pmatrix} = C_p\begin{pmatrix} p_w \\ 1 \end{pmatrix} \tag{65}$$

can be rearranged into the 3×4 linear homogeneous system

$$\begin{pmatrix} C_c^1 - x_p C_c^3 \\ C_c^2 - y_p C_c^3 \\ C_p^1 - x_x C_c^3 \end{pmatrix} \begin{pmatrix} \alpha p_w \\ \alpha \end{pmatrix} = 0 \tag{66}$$

[0349] A solution to eq. (66) can be obtained (for non-limiting example) using SVD and the estimate of p_w obtained from the homogeneous solution to eq. (66).

[0350] When there are a large number of points to process, computational savings can be made. A generalization of the vector cross-produce for n−1 vectors in an n-dimensional linear space can be defined implicitly by $(w, v_1\times \ldots \times v_{n-1}) =\det(v_1, \ldots v_{n-1}, w)$. $v_1\times \ldots \times v_{n-1}$ can be written as $\Sigma_1 \det(v_1, \ldots v_{n-1}, e_k)e_k$ and is orthogonal to v_k where $\{e_k\})_{k=1}{}^n$ are the standard basis vectors of $\mathfrak{R}^n$. Therefore, a solution to eq. (66) is given by the (generalized) cross product of the rows of the 3×4 matrix

$$\begin{pmatrix} \alpha p_w \\ \alpha \end{pmatrix} = \sum_{k=1}^{4} \det(C_r^1 - x_p C_c^3, C_r^2 - y_p C_r^3, C_p^1 - x_c C_p^2, e_k)e_k \tag{67}$$

[0351] Dividing by α and using the linearity and antisymmetry of the determinant tensor, the kth component of p_w is given by

$$p_w^k = \frac{C_{1,2,1}^k - x_p C_{3,2,1}^k - y_p C_{1,3,1}^k - x_s C_{1,2,2}^k + x_s x_p C_{3,2,2}^k + x_s y_p C_{1,3,2}^k}{C_{1,2,1}^4 - x_p C_{3,2,1}^4 - y_p C_{1,3,1}^4 - x_s C_{1,2,2}^4 + x_s x_p C_{3,2,2}^4 + x_s y_p C_{1,3,2}^4} \tag{68}$$

where $C_{i,j,l}{}^k=\det(C_c{}^i,C_c{}^j,C_p{}^l,e_k)$ are constants which depend only on the camera and projector PTMs and can be precomputed.

[0352] In these experiments, the system comprised a K2T LCS and controller housed in a Kodak projector. TM-6CN Pulnix camera and S2200 Data Cell framegrabber. The LCS shutter has 256 stripes and 512×512 images were captured. The calibration reference is a 150 mm cube with 72 fiducial marks of 5 mm radius arranged over 3 faces, as shown in FIG. **18**. The 3D location of each fiducial mark centroid has been measured to an accuracy of 0.1 mm in a coordinate system attached to the cube. During calibration, this coordinate system is taken to be the world coordinates system. Calibration thus fixes the world coordinate system and all subsequent measurements are expressed in the world coordinates system. The experimental setup has the projector above the camera with the angle between their optic axes being approximately 12° to give a working volume of 250 mm diameter at 1600 mm in front of the camera.

[0353] To evaluate the performance of the system, seven trials were used with the calibration reference in a different position in each. For each trial, the observed data consists of the pixel coordinates and stripe values of the fiducial marks. The calibration parameters for each trial were extracted from the observed data using the procedure described hereinabove.

[0354] The estimated pixel coordinates and stripe values are obtained by projecting the world reference coordinates using the calibrated system model. The pixel residuals (FIG. **19**) and stripe residuals (FIG. **20**) are the difference between the measured and estimated values. The spatial intersection errors (FIG. **21**) are the difference between the reference coordinates of the fiducial marks and their coordinates estimated by special intersection. FIGS. **19**, **20** and **21** show the pixel residuals, stripe residuals and spatial intersection errors for trial **4**. The fiducial mark numbers in FIG. **21** were obtained from an arbitrary ordering of the fiducial marks on the cube.

[0355] Table 3 shows the average magnitude of the special intersection errors for each of the calibration trials. Each average was obtained using all 72 fiducial marks. For comparison, Table 4 shows the average errors when radial distortion is neglected for the camera and projector models. Table 5 shows the average errors when no substripe estimation is used. Excluding either radial distortion or substripe estimation increases the error in all trials. On average, over all trials, adding substripe estimation improves the performance by 82% while adding lens distortion improves the performance by only 13%, showing that substripe estimation has the more significant effect.

TABLE 3

Average magnitude of the spatial intersection error for calibration trials.

Trial	1	2	3	4	5	6	7
average error (mm)	0.154	0.245	0.296	0.187	0.280	0.246	0.233

TABLE 4

Average magnitude of the spatial intersection error for calibration trials if radial distortion is neglected.

Trial	1	2	3	4	5	6	7
average error (mm)	0.226	0.283	0.311	0.223	0.292	0.261	0.264

TABLE 5

Average magnitude of the spatial intersection error for calibration trials with no substripe estimation.

Trial	1	2	3	4	5	6	7
average error (mm)	1.348	1.312	1.371	1.521	1.233	1.170	1.444

[0356] Given the observed data for a trial and the calibration parameters for that trial (or any other), special intersection can be used to estimate the coordinates of the fiducial marks in the world coordinate system established by the calibration. These can be compared with the reference coordinates by estimating, using (for non-limiting example) a least squares error criterion, the 3D rigid body transformation needed to transform the reference coordinates to the estimated coordinates (model fitting). The model fitting error is the difference between the estimated world coordinates and the transformed reference coordinates. Table 6 shows the average magnitude of the model fitting error for all of the calibration trials and all of the observed data sets. The diagonal entries of Table 6 are very close to, and less than, the values in Table 3. This indicates that the spatial intersection procedure is accurately recovering the coordinates in the world coordinate system. The model fitting errors are largest when the spatial intersection data set is farthest from the calibration data set.

TABLE 6

Average magnitude of the model fitting error (in mm) for each calibration trial (rows) and each measured data set (columns).

trial	1	2	3	4	5	6	7
1	0.154	0.405	0.271	0.207	0.322	0.285	0.298
2	0.389	0.245	0.445	0.337	0.246	0.428	0.392
3	0.335	0.613	0.296	0.367	0.490	0.307	0.437
4	0.205	0.379	0.312	0.187	0.298	0.297	0.248
5	0.408	0.301	0.476	0.349	0.280	0.451	0.374
6	0.324	0.564	0.273	0.355	0.455	0.245	0.424
7	0.295	0.475	0.308	0.247	0.366	0.292	0.233

[0357] Table 7 shows the intrinsic parameters for the system obtained from each trial. The camera scale factors obtained during calibration agree with the nominal value of 2200 pixels/mm. In addition, the camera principal point is consistent with the nominal value of (255,255) pixels. The shear coefficient is small with respect to t. (0.14%), suggesting a very small contribution. The scale factor for the projector is close to the nominal value of 120 stripes/mm.

TABLE 7

The 6 intrinsic parameters for the camera (upper) and the 3 intrinsic parameters for the projector (lower) for each calibration trial.

trial	1	2	3	4	5	6	?⃝
s_c^x	2411.062	2399.667	2425.255	2418.480	2403.901	2443.054	24(?⃝
s_c^y	2412.349	2402.982	2425.084	2421.023	2407.875	2445.911	241?⃝
c_c^x	289.389	283.201	301.069	274.053	271.295	314.980	272?⃝
c_c^y	271.802	303.288	258.478	275.559	309.616	261.080	25(?⃝
k_c	4.211	2.316	4.308	3.285	1.938	4.006	3?⃝
K_c	0.464	0.176	0.449	0.439	0. 200	0.219	0?⃝
s_p^x	899.157	1020.565	1151.871	1015.006	1061.455	1162.614	10(?⃝
c_p^x	159.906	240.831	130.128	183.441	223.480	132.600	181?⃝
K_p	0.085	0.123	0.317	0.116	0.138	0.384	0?⃝

?⃝ indicates text missing or illegible when filed

[0358] However, there are significant variations in many of the parameters. An examination of the estimated dispersion matrix for the camera shows some parameters have high variances and there are high correlations between parameters. This can be partially explained by the experimental configuration of the structured light system; with the distance between the camera and the world reference much larger than the diameter of the world reference a weak perspective camera model provides a reasonable explanation of the observed data. Consequently many parameters are correlated. In particular, T_c^3 has a relatively large variance and is highly correlated with s_c^x and s_c^y.

[0359] The above remarks are also applicable to the projector parameters. However, the situation for the projector is inherently worse than that for the camera as the projector has nine parameters (compared to 12 for the camera) but only half as many data points are available. As described above, introducing K_p allows T_p^2 to be estimated, but, as expected, it has a large variance. Furthermore, when the distance between the projector and the world reference is much larger than the diameter of the world reference, the stripe planes are nearly parallel in the working volume. Hence a component of the rotation is nearly unidentifiable. This gives rise to large variances in the rotation parameters.

[0360] It is important to note that the actual values of the camera and projector parameters are incidental in this situation and it is the values of the measured 3D coordinates that are of interest.

[0361] Therefore, including T_p^2 and K_p in the projector model is useful because it improves the accuracy of the spatial data, even though T_p^2 is not particularly accurate.

[0362] In preferred embodiments, optical fibers are used to transmit the modulated light through the endoscope to the region of interest, so that the effective area of the projector is minimized.

[0363] In preferred embodiments, calibration of the system is carried out when the system is produced. Preferably, no recalibration is needed. However, if recalibration is needed, it can be carried out on site, even in the operating theater.

[0364] In preferred embodiments, a standard camera can be used, with positioning of the camera field of view controlled by positioning the endoscope.

[0365] A further advantage of the system of the present invention is that standard systems can b used to transmit the modulated light to the region of interest, for example, through the endoscope or laparoscope, or through a thoracostomy.

[0366] In preferred embodiments of the system, a standard endoscope is used. In preferred embodiments, the light source is a laser; the location from which the light enters the working area can be altered so as to produce the stripe pattern needed for reconstruction disclosed above.

[0367] In embodiments using the reconstruction method disclosed above, the axis of the wide-angle lens is not parallel to the plane formed by the stripe pattern since as described above, reconstruction is not possible when a ray between the camera focal point and the object point (parallel to the axis of the lens) is parallel to the plane originating at the projector focal point and passing through the object point (the plane formed by the stripe pattern).

[0368] In some embodiments of the system, in addition to live-streaming the images, the system can capture still images and store them in a database.

[0369] In some embodiments, the light source can be at least one spectral range selected from a group consisting of the visible, near infrared, infrared, or ultraviolet spectral regions.

[0370] Image transmission can be by using any of wireless communication, transmission of optical signals through fiber optic cables, or transmission of electrical signals through wires or cables.

[0371] The light source can be a laser, Light Emitting Diodes (LED's) or any other source known in the art. Preferably the illumination is in substantially the same spectral range as that to which the camera is sensitive.

[0372] Color Modulation

[0373] Color modulation can be used to distinguish different types of tissue, since different types of tissue show different patterns of scattering and absorption at different wavelengths due to the different fractions of e.g., lipids, deoxyhemoglobin (HHb), oxyhemoglobin (O_2Hb) and water in the tissues. FIG. **22** shows absorption patterns for lipids, deoxyhemoglobin (HHb), oxyhemoglobin (O_2Hb) and water as a function of wavelength for wavelengths from about 650 nm to about 1000 nm.

[0374] Color modulation can be used to identify hemodynamics and vascular reactivity, aiding in diagnosis of cancerous tissue and vascular disease. For non-limiting example, in vascular disease, the restricted blood flow to the tissue results in ischemia, hypoxia and tissue necrosis, all identifiable by increased HHb and decreased O_2Hb.

[0375] An example of the difference between normal tissue and cancerous tissue is shown in FIG. **23**, in which, for 58 subjects, the absorption pattern for normal (**2320**) and cancerous (**2310**) breast tissue is compared. The absorption pattern between about 650 nm and 850 nm is primarily due to HHb and O_2Hb, whereas the absorption pattern between about 850 nm and about 1000 nm is primarily due to H_2O and lipids.

[0376] FIG. **24** shows the difference between cancerous (dashed arrows) and normal tissue (solid arrows) for 65 subjects. The curve for the normal subjects is nearly flat, while the curve for the cancerous tissue shows a peak and trough characteristic of Hb, a lipid trough and water peak.

[0377] FIG. **25** shows the difference between cancerous (dashed arrows) and fibroadenomous tissue (dotted arrows) for 40 subjects. The peak and trough characteristic of Hb, the lipid trough and the water peak are significantly larger for the cancerous than the fibroadenomous tissue.

[0378] Control of the Field of View

[0379] In some embodiments, the device of the present invention additionally comprises a touchscreen used as the display screen on which the image of the field of view of the laparoscope is displayed. In these embodiments, in order to direct the laparoscope, the surgeon touches the portion of the image toward which he wants the laparoscope to move and automatic control software controls the motion of the laparoscope towards the goal. Thus, in preferred embodiments, the surgeon need not concern himself with the mechanics of repositioning; a brief touch on the display screen and he can return his hand to the instrument while the laparoscope automatically repositions itself.

[0380] In preferred variants of embodiments including a touchscreen, the surgeon directs the instrument to the desired location by touching the portion of the screen showing the image of the desired location. For example, to direct the laparoscope to put the tip of the appendix in the center of the screen, the surgeon would touch the image of the tip of appendix on the screen. In these embodiments, the surgeon touches the screen only briefly; continued pressure is not needed to direct the laparoscope to the desired position.

[0381] In other variants of embodiments including a touchscreen, the screen contains at least one graphical direction indicator, which can be at least one arrow, line or pointer or, preferably, a direction rose with 4, 8 or 16 indicators. In some variants of these embodiments, the surgeon touches the appropriate indicator, for non-limiting example, the one pointing at 45° clockwise from the vertical, and the laparoscope moves so that the center of its field of view moves towards the upper right portion of the image. In these embodiments, the surgeon needs to keep his hand on the touchscreen until the maneuver is complete.

[0382] In other variants of embodiments with graphical indicators on the touchscreen, the indicator comprises a direction rose (**100**), the surgeon touches a position anywhere on the graphical indicator and the laparoscope moves so that the center of its field of view moves towards the direction indicated by the position of the touch. For example, in the direction rose (**100**) shown in FIG. **26**, the uppermost point (**110**) indicates movement towards the top of the screen, the rightmost point (**120**), movement towards the right, the lowest point (**130**), movement towards the bottom of the screen, and the leftmost point (**140**), movement towards the left. If the surgeon touches a position 55° clockwise from the vertical, the laparoscope will move so that the center of its field of view moves towards the upper right portion of the image, at an angle 55° clockwise from the vertical. In these embodiments, the surgeon needs to keep his hand on the touchscreen until the maneuver is complete.

[0383] In other variants of embodiments with graphical indicators on the touchscreen, the location of the touch on the indicator defines the speed at which the center of the field of view moves. For non-limiting example, the further from the center of the direction rose, the faster the motion.

[0384] In yet other embodiments with a touchscreen, the direction of motion is indicated by words appearing on the screen such as, but not limited to, left, right, up, down, forward, back, zoom, zoom in, zoom out, and any combination thereof.

[0385] Combinations of the above embodiments will be obvious to one skilled in the art.

[0386] Many other means of indication direction of movement via a touchscreen will be obvious to one skilled in the art.

[0387] In yet other embodiments, voice commands are used to direct the endoscope. In such embodiments, the direction of motion can be indicated by words spoken by the surgeon such as, but not limited to, left, right, up, down, forward, back, zoom, zoom in, zoom out, and any combination thereof.

[0388] In some variants of embodiments employing voice commands, the surgeon can provide an angular designation, such as, but not limited to, a numerical value or a compass rose designation.

[0389] Non-limiting examples of numerical values include 60°, 75° clockwise, 30° west of north. Other examples will be obvious to one skilled in the art. Non-limiting examples of compass rose designations are north-northwest, NNW, and southeast by south.

[0390] In still other embodiments, eye movements are used to direct the endoscope. Typically, in such embodiments, the endoscope moves in the direction in which the surgeon moves his eyes. For non-limiting example, if the surgeon looks to the right, the endoscope moves to the right of the field of view, if the surgeon looks up, the endoscope moves towards the top of the field of view, and similarly for eye movements to the left or downward.

[0391] According to different embodiments of the present invention, the surgical controlling system comprises the following components:

> **[0392]** a. at least one surgical tool adapted to be inserted into a surgical environment of a human body for assisting a surgical procedure, at least one said tool being an articulating tool;
>
> **[0393]** b. at least one location estimating means adapted to real-time estimate/locate the location (i.e., the 3D spatial position) of the at least one surgical tool at any given time t;
>
> **[0394]** c. at least one movement detection means communicable with a movement-database and with said location estimating means; said movement-database is adapted to store said 3D spatial position of said at least one surgical tool at time t_f and at time t_0; where $t_f > t_0$; said movement detection means is adapted to detect movement of said at least one surgical tool if the 3D spatial position of said at least one surgical tool at time t_f is different than said 3D spatial position of said at least one surgical tool at time t_O, and,
>
> **[0395]** d. a controller having a processing means communicable with a database, the controller adapted to control the spatial position of the at least one surgical tool.

[0396] The initial time t_0 can be the beginning of the surgical procedure, it can be the time at which the tool entered the body, it can be the time at the beginning of the current movement, or it can be the previous timestep in the current maneuver. In preferred embodiments, the processor will reset t_0 as necessary during the surgical procedure. For non-limiting example, the difference in position between the location of the tool at the previous timestep and its location at the current timestep can be used to calculate the tool's current velocity while the difference in position between its current position and its position at the start of the current maneuver can be used to calculate the tool's overall direction of motion.

[0397] The location of the tool can be the location of the tool's tip, the location of a predetermined point on the tool's body, or the location of a predetermined point on the tool's handle. The position defining the location of the tool can be changed as needed, e.g., from the location of the body to the location of the tip.

[0398] In some embodiments, the surgical controlling system additionally comprises a touchscreen adapted to accept input of a location within the body, that location indicated by pressure on the portion of the touchscreen showing the image of the location.

[0399] In order to facilitate control, a number of motion control rules have been implemented, as described hereinbelow.

[0400] It is within the scope of the present invention that the database is adapted to store a predetermined set of rules according to which ALLOWED and RESTRICTED movements of the at least one surgical tool are determined, such that the spatial position of the at least one surgical tool is controlled by the controller according to the ALLOWED and RESTRICTED movements.

[0401] In other words, each detected movement by said movement detection means of said at least one surgical tool is determined as either an ALLOWED movement or as a RESTRICTED movement according to said predetermined set of rules.

[0402] Thus, the present invention stores the 3D spatial position of each surgical tool at a current at time t_f and at time t_0; where $t_f > t_0$. If the 3D spatial position of said at least one surgical tool at time t_f is different than said 3D spatial position of said at least one surgical tool at time t_O movement of the tool is detected. Next the system analyses said movement according to said set of rule and process whether said movement is ALLOWED movement or RESTRICTED movement.

[0403] According to one embodiment of the present invention, the system prevents said movement, if said movement is a RESTRICTED movement. Said movement prevention is obtained by controlling a maneuvering system which prevents the movement of said surgical tool.

[0404] According to one embodiment of the present invention, the system does not prevent said movement, (if said movement is a RESTRICTED movement), but merely signals/alerts the user (i.e., the physician) of said RESTRICTED movement.

[0405] According to another embodiment of the present invention, said surgical tool is an endoscope.

[0406] According to different embodiments of the present invention, the controller may provide a suggestion to the operator as to which direction the surgical tool has to move to or may be moved to.

[0407] Thus, according to a preferred embodiment of the present invention, the present invention provides a predetermined set of rules which define what is an "ALLOWED movement" of any surgical tool within the surgical environment and what is a "RESTRICTED movement" of any surgical tool within the surgical environment.

[0408] According to some embodiments the system of the present invention comprises a maneuvering subsystem communicable with the controller, the maneuvering subsystem is adapted to spatially reposition the at least one surgical tool during surgery according to the predetermined set of rules.

[0409] According to some embodiments, the controller may provide instructions to a maneuvering subsystem for spatially repositioning the location of the surgical tool. According to these instructions, only ALLOWED movements of the surgical tool will be performed. Preventing RESTRICTED movements is performed by: detecting the location of the surgical tool; processing all current rules; analyzing the movement of the surgical tool and preventing the movement if the tool's movement is a RESTRICTED movement.

[0410] According to some embodiments, system merely alerts the physician of a RESTRICTED movement of at least one surgical tool (instead of preventing said RESTRICTED movement).

[0411] Alerting the physician of RESTRICTED movements (or, alternatively preventing a RESTRICTED movement) is performed by: detecting the location of the surgical tool; processing all current rules; analyzing the movement of the surgical tool and informing the surgeon (the user of the system) if the tool's movement is an ALLOWED movement or a RESTRICTED movement.

[0412] Thus, according to a preferred embodiment of the present invention, if RESTRICTED movements are prevented, the same process (of detecting the location of the surgical tool; processing all current rules and analyzing the movement of the surgical tool) is followed except for the last movement, where the movement is prevented if the tool's movement is a RESTRICTED movement. The surgeon can also be informed that the movement is being prevented.

[0413] According to another embodiment, the above (alerting the physician and/or preventing the movement) is performed by detecting the location of the surgical tool and analyzing the surgical environment of the surgical tool. Following analysis of the surgical environment and detection of the location of the surgical tool, the system may assess all the risks which may follow a movement of the surgical tool in the predetermined direction. Therefore, each location in the surgical environment has to be analyzed so that any possible movement of the surgical tool will be classified as an ALLOWED movement or a RESTRICTED movement.

[0414] According to one embodiment of the present invention, the location of each tool is determined using image processing means and determining in real-time what is the 3D spatial location of each tool. It should be understood that the above mentioned "tool" may refer to the any location on the tool. For example, it can refer to the tip of the same, the body of the same and any combination thereof.

[0415] In some embodiments, avoidance of body organs is facilitated by means of a proximity sensor on the circumference of at least one tool. In these embodiments, if the distance between the tool and another object in the surgical environment, such as, but not limited to, an organ or another tool, is less than a predetermined distance, the proximity sensor activates, thereby notifying the control system that at least one tool is too close to another object in the surgical environment.

[0416] In some variants of embodiments with proximity sensors, the proximity sensor not only determined whether an object is within a predetermined distance of the sensor, it also determines, for objects within the predetermined distance, the distance between the sensor and the object.

[0417] Hereinbelow, determination of the 3D location of each tool includes determination by means of a proximity sensor as well as determination by means of image processing.

[0418] The predetermined set of rules which are the essence of the present invention are adapted to take into consideration all the possible factors which may be important during the surgical procedure. The predetermined set of rules may comprise the following rules or any combination thereof:

[0419] a. a route rule;
[0420] b. an environment rule;
[0421] c. an operator input rule;
[0422] d. a proximity rule;
[0423] e. a collision prevention rule;
[0424] f. a history based rule;
[0425] g. a tool-dependent ALLOWED and RESTRICTED movements rule.
[0426] h. a most used tool rule;
[0427] i. a right tool rule;
[0428] j. a left tool rule;
[0429] k. a field of view rule;
[0430] l. a no fly zone rule;
[0431] m. an operator input rule;
[0432] n. a preferred volume zone rule;
[0433] o. a preferred tool rule;
[0434] p. a movement detection rule, and
[0435] q. a tagged tool rule.

[0436] Thus, for example, the collision prevention rule defines a minimum distance below which two or more tools should not be brought together (i.e., there is minimum distance between two or more tools that should be maintained). If the movement of one tool will cause it to come dangerously close to another tool (i.e., the distance between them, after the movement, is smaller than the minimum distance defined by the collision prevention rule), the controller either alerts the user that the movement is a RESTRICTED movement or does not permit the movement.

[0437] It should be emphasized that all of the above (and the following disclosure) is enabled by constantly monitoring the surgical environment, and identifying and locating the 3D spatial location of each element/tool in the surgical environment.

[0438] The identification is provided by conventional means known to any skilled in the art (e.g., image processing, optical means etc.).

[0439] The following provides explanations for each of the above mentioned rules and its functions:

[0440] According to some embodiments, the route rule comprises a predefined route in which the at least one surgical tool is adapted to move within the surgical environment; the ALLOWED movements are movements in which the at least one surgical tool is located within the borders of the predefined route, and the RESTRICTED movements are movements in which the at least one surgical tool is located out of the borders of the predefined route. Thus, according to this embodiment, the route rule comprises a communicable database storing at least one predefined route in which the at least one surgical tool is adapted to move within the surgical environment; the predefined route comprises n 3D spatial positions of the at least one surgical tool in the route; n is an integer greater than or equal to 2; ALLOWED movements are movements in which the at least one surgical tool is located substantially in at least one of the n 3D spatial positions of the predefined route, and RESTRICTED movements are movements in which the location of the at least one surgical tool is substantially different from the n 3D spatial positions of the predefined route.

[0441] In other words, according to the route rule, each of the surgical tool's courses (and path in any surgical procedure) is stored in a communicable database. ALLOWED movements are defined as movements in which the at least one surgical tool is located substantially in at least one of the stored routes; and RESTRICTED movements are movements in which the at least one surgical tool is in a substantially different location than any location in any stored route.

[0442] According to some embodiments, the environmental rule is adapted to determine ALLOWED and RESTRICTED movements according to hazards or obstacles in the surgical environment as received from an endoscope or other sensing means. Thus, according to this embodiment, the environmental rule comprises a comprises a communicable database; the communicable database is adapted to received real-time images of the surgical environment and is adapted to perform real-time image processing of the same and to determine the 3D spatial position of hazards or obstacles in the surgical environment; the environmental rule is adapted to determine ALLOWED and RESTRICTED movements according to hazards or obstacles in the surgical environment, such that RESTRICTED movements are movements in which at least one surgical tool is located substantially in at least one of the 3D spatial positions, and ALLOWED movements are movements in which the location of at least one surgical tool is substantially different from the 3D spatial positions.

[0443] In other words, according to the environment rule, each element in the surgical environment is identified so as to establish which is a hazard or obstacle (and a path in any surgical procedure) and each hazard and obstacle (and path) is stored in a communicable database. RESTRICTED movements are defined as movements in which the at least one surgical tool is located substantially in the same location as that of the hazards or obstacles; and the ALLOWED movements are movements in which the location of the at least one surgical tool is substantially different from that of all of the hazards or obstacles.

[0444] According to other embodiments, hazards and obstacles in the surgical environment are selected from a group consisting of tissues, surgical tools, organs, endoscopes and any combination thereof.

[0445] According to some embodiments, the operator input rule is adapted to receive an input from the operator of the system regarding the ALLOWED and RESTRICTED movements of the at least one surgical tool. Thus, according to this embodiment, the operator input rule comprises a communicable database; the communicable database is adapted to receive an input from the operator of the system regarding ALLOWED and RESTRICTED movements of the at least one surgical tool.

[0446] According to other embodiments, the input comprises n 3D spatial positions; n is an integer greater than or equal to 2; wherein at least one of which is defined as an ALLOWED location and at least one of which is defined as a RESTRICTED location, such that the ALLOWED movements are movements in which the at least one surgical tool is located substantially in at least one of the n 3D ALLOWED spatial positions, and the RESTRICTED movements are movements in which the location of the at least one surgical tool is substantially different from the n 3D ALLOWED spatial positions.

[0447] According to other embodiments, the input comprises at least one rule according to which ALLOWED and RESTRICTED movements of the at least one surgical tool are determined, such that the spatial position of the at least one surgical tool is controlled by the controller according to the ALLOWED and RESTRICTED movements.

[0448] According to other embodiments, the operator input rule can convert an ALLOWED movement to a RESTRICTED movement and a RESTRICTED movement to an ALLOWED movement.

[0449] According to some embodiments, the proximity rule is adapted to define a predetermined distance between the at least one surgical tool and at least one another surgical tool; the ALLOWED movements are movements which are within the range or out of the range of the predetermined distance, and the RESTRICTED movements which are out of the range or within the range of the predetermined distance; the ALLOWED movements and the RESTRICTED movements are defined according to different ranges. Thus, according to this embodiment, the proximity rule is adapted to define a predetermined distance between at least two surgical tools. In a preferred embodiment, the ALLOWED movements are movements which are within the range of the predetermined distance, while the RESTRICTED movements which are out of the range of the predetermined distance. In another preferred embodiment, the ALLOWED movements are movements which are out of the range of the predetermined distance, while the RESTRICTED movements are within the range of the predetermined distance

[0450] It should be pointed out that the above mentioned distance can be selected from the following:

[0451] (a) the distance between the tip of the first tool and the tip of the second tool;

[0452] (b) the distance between the body of the first tool and the tip of the second tool;

[0453] (c) the distance between the body of the first tool and the body of the second tool;

[0454] (d) the distance between the tip of the first tool and the body of the second tool; and any combination thereof

[0455] According to another embodiment, the proximity rule is adapted to define a predetermined angle between at least three surgical tools; ALLOWED movements are movements which are within the range or out of the range of the predetermined angle, and RESTRICTED movements are movements which are out of the range or within the range of the predetermined angle.

[0456] According to some embodiments, the collision prevention rule is adapted to define a predetermined distance between the at least one surgical tool and an anatomical element within the surgical environment (e.g. tissue, organ, another surgical tool or any combination thereof); the ALLOWED movements are movements which are in a range that is larger than the predetermined distance, and the RESTRICTED movements are movements which is in a range that is smaller than the predetermined distance.

[0457] According to another embodiment, the anatomical element is selected from a group consisting of tissue, organ, another surgical tool or any combination thereof.

[0458] According to some embodiments, the surgical tool is an endoscope. The endoscope is adapted to provide real-time images of the surgical environment.

[0459] According to some embodiments, the right tool rule is adapted to determine the ALLOWED movement of the endoscope according to the movement of a surgical tool in a specified position in relation to the endoscope, preferably positioned to right of the same. According to this rule, the tool which is defined as the right tool is constantly tracked by the endoscope. According to some embodiments, the right tool is defined as the tool positioned to the right of the endoscope; according to other embodiments, any tool can be defined as the right tool. An ALLOWED movement, according to the right tool rule, is a movement in which the endoscope field of view is moved to a location substantially the same as the location of the right tool, thereby tracking the right tool. A RESTRICTED movement, according to the right tool rule, is a movement in which the endoscope field of view is moved to a location substantially different from the location of the right tool.

[0460] According to some embodiments, the left tool rule is adapted to determine the ALLOWED movement of the endoscope according to the movement of a surgical tool in a specified position in relation to the endoscope, preferably positioned to left of the same. According to this rule, the tool which is defined as the left tool is constantly tracked by the endoscope. According to some embodiments, the left tool is defined as the tool positioned to the left of the endoscope; according to other embodiments, any tool can be defined as the left tool. An ALLOWED movement, according to the left tool rule, is a movement in which the endoscope field of view is moved to a location substantially the same as the location of the left tool. A RESTRICTED movement, according to the left tool rule, is a movement in which the endoscope field of view is moved to a location substantially different from the location of the left tool.

[0461] According to some embodiments, the field of view rule is adapted to define a field of view and maintain that field of view. The field of view rule is defined such that if the endoscope is adapted to track a predetermined set of tools in a desired field of view, when one of those tools is no longer in the field of view, the rule instructs the endoscope to zoom out so as to reintroduce the tool into the field of view. Thus, according to this embodiment, the field of view rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the combination of all of the n 3D spatial positions provides a predetermined field of view; the field of view rule is adapted to determine the ALLOWED movement of the endoscope within the n 3D spatial positions so as to maintain a constant field of view, such that the ALLOWED movements are movements in which the endoscope is located substantially in at least one of the n 3D spatial positions, and the RESTRICTED movements are movements in which the location of the endoscope is substantially different from the n 3D spatial positions.

[0462] Thus, according to another embodiment of the field of view rule, the field of view rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the combination of all of the n 3D spatial positions provides a predetermined field of view. The field of view rule further comprises a communicable database of m tools and the 3D spatial locations of the same, where m is an integer greater than or equal to 1 and where a tool can be a surgical tool, an anatomical element and any combination thereof. The combination of all of the n 3D spatial positions provides a predetermined field of view. The field of view rule is adapted to determine ALLOWED movement of the endoscope such that the m 3D spatial positions of the tools comprise at least one of the n 3D spatial positions of the field of view, and RESTRICTED movements are movements in which the 3D spatial position of at least one tool is substantially different from the n 3D spatial positions of the field of view.

[0463] According to another embodiment, the preferred volume zone rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the n 3D spatial positions provides the preferred volume zone; the preferred volume zone rule is adapted to determine the ALLOWED movement of the endoscope within the n 3D spatial positions and RESTRICTED movement of the endoscope outside the n 3D spatial positions, such that the ALLOWED movements are movements in which the endoscope is located substantially in at least one of the n 3D spatial positions, and the RESTRICTED movements are movements in which the location of the endoscope is substantially different from the n 3D spatial positions. In other words, the preferred volume zone rule defines a volume of interest (a desired volume of interest), such that an ALLOWED movement, according to the preferred volume zone rule, is a movement in which the endoscope (or any surgical tool) is moved to a location within the defined preferred volume. A RESTRICTED movement, according to the preferred volume zone rule, is a movement in which the endoscope (or any surgical tool) is moved to a location outside the defined preferred volume.

[0464] According to another embodiment, the preferred tool rule comprises a communicable database, the database stores a preferred tool; the preferred tool rule is adapted to determine the ALLOWED movement of the endoscope according to the movement of the preferred tool. In other words, the preferred tool rule defines a preferred tool (i.e., a tool of interest) that the user of the system wishes to track. An ALLOWED movement, according to the preferred tool rule, is a movement in which the endoscope is moved to a location substantially the same as the location of the preferred tool. A RESTRICTED movement is a movement in which the endoscope is moved to a location substantially different from the location of the preferred tool. Thus, according to the preferred tool rule the endoscope constantly tracks the preferred tool, such that the field of view, as seen from the endoscope, is constantly the preferred tool. It should be noted that the user may define in said preferred tool rule to constantly track the tip of said preferred tool or alternatively, the user may define in said preferred tool rule to constantly track the body or any location on the preferred tool.

[0465] According to some embodiments, the no fly zone rule is adapted to define a RESTRICTED zone into which no tool (or alternatively no predefined tool) is permitted to enter. Thus, according to this embodiment, the no fly zone rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the n 3D spatial positions define a predetermined volume within the surgical environment; the no fly zone rule is adapted to determine a RESTRICTED movement if the movement is within the no fly zone and an ALLOWED movement if the movement is outside the no fly zone, such that RESTRICTED movements are movements in which the at least one surgical tool is located substantially in at least one of the n 3D spatial positions, and the ALLOWED movements are movements in which the location of the at least one surgical tool is substantially different from the n 3D spatial positions.

[0466] According to another embodiment, the most used tool rule is adapted to define (either real-time, during the procedure or prior to the procedure) which tool is the most used tool (i.e., the tool which is moved the most during the procedure) and to instruct the maneuvering subsystem to constantly position the endoscope to track the movement of this tool. Thus, according to this embodiment, the most used tool rule comprises a communicable database counting the number of movements of each of the surgical tools; the most used tool rule is adapted to constantly position the endoscope to track the movement of the surgical tool with the largest number of movements. In another embodiment of the most used tool rule, the communicable database measures the amount of movement of each of the surgical tools; the most used tool rule is adapted to constantly position the endoscope to track the movement of the surgical tool with the largest amount of movement.

[0467] According to another embodiment, the system is adapted to alert the physician of a RESTRICTED movement of at least one surgical tool. The alert can be audio signaling, voice signaling, light signaling, flashing signaling and any combination thereof.

[0468] According to another embodiment, an ALLOWED movement is one permitted by the controller and a RESTRICTED movement is one denied by the controller.

[0469] According to another embodiment, the operator input rule is adapted to receive an input from the operator of the system regarding ALLOWED and RESTRICTED movements of the at least one surgical tool. In other words, the operator input rule receives instructions from the physician as to what can be regarded as ALLOWED movements and what are RESTRICTED movements. According to another embodiment, the operator input rule is adapted to convert an ALLOWED movement to a RESTRICTED movement and a RESTRICTED movement to an ALLOWED movement.

[0470] According to some embodiments, the history-based rule is adapted to determine the ALLOWED and RESTRICTED movements according to historical movements of the at least one surgical tool in at least one previous surgery. Thus, according to this embodiment, the history-based rule comprises a communicable database storing each 3D spatial position of each of the surgical tools, such that each movement of each surgical tool is stored; the history-based rule is adapted to determine ALLOWED and RESTRICTED movements according to historical movements of the at least one surgical tool, such that the ALLOWED movements are movements in which the at least one surgical tool is located substantially in at least one of the 3D spatial positions, and the RESTRICTED movements are movements in which the location of the at least one surgical tool is substantially different from the n 3D spatial positions.

[0471] According to some embodiments, the tool-dependent ALLOWED and RESTRICTED movements rule is adapted to determine ALLOWED and RESTRICTED movements according to predetermined characteristics of the surgical tool, where the predetermined characteristics of the surgical tool are selected from a group consisting of: physical dimensions, structure, weight, sharpness, and any combination thereof. Thus, according to this embodiment, the tool-dependent ALLOWED and RESTRICTED movements rule comprises a communicable database; the communicable database is adapted to store predetermined characteristics of at least one of the surgical tools; the tool-dependent ALLOWED and RESTRICTED movements rule is adapted to determine ALLOWED and RESTRICTED movements according to the predetermined characteristics of the surgical tool.

[0472] According to another embodiment, the predetermined characteristics of the surgical tool are selected from a group consisting of: physical dimensions, structure, weight, sharpness, and any combination thereof.

[0473] According to this embodiment, the user can define, e.g., the structure of the surgical tool he wishes the endoscope to track. Thus, according to the tool-dependent ALLOWED and RESTRICTED movements rule the endoscope constantly tracks the surgical tool having said predetermined characteristics as defined by the user.

[0474] According to another embodiment of the present invention, the movement detection rule comprises a communicable database comprising the real-time 3D spatial positions of each surgical tool; said movement detection rule is adapted to detect movement of at least one surgical tool. When a change in the 3D spatial position of that surgical tool is received, ALLOWED movements are movements in which the endoscope is re-directed to focus on the moving surgical tool.

[0475] According to another embodiment of the present invention, the tagged tool rule comprises means of tagging at least one surgical tool within the surgical environment such that, by maneuvering the endoscope, the endoscope is constantly directed to the tagged surgical tool. Thus, according to the tagged tool rule, the endoscope constantly tracks the preferred (i.e., tagged) tool, such that the field of view, as seen from the endoscope, is constantly maintained on the preferred (tagged) tool. It should be noted that the user can define the tagged tool rule to constantly track the tip of the preferred (tagged) tool, the body of the preferred (tagged) tool, or any other location on the preferred (tagged) tool.

[0476] According to another embodiment of the present invention, the system further comprises a maneuvering subsystem communicable with the controller. The maneuvering subsystem is adapted to spatially reposition the at least one surgical tool during a surgery according to the predetermined set of rules.

[0477] According to some embodiments, the at least one location estimating means is at least one endoscope adapted to acquire real-time images of a surgical environment within the human body for the estimation of the location of at least one surgical tool.

[0478] According to another embodiment, the location estimating means comprise at least one selected from a group consisting of optical imaging means, radio frequency transmitting and receiving means, at least one mark on at least one surgical tool and any combination thereof.

[0479] According to another embodiment, the at least one location estimating means is an interface subsystem between a surgeon and at least one surgical tool, the interface subsystem comprising (a) at least one array comprising N regular light sources or N pattern light sources, where N is a positive integer; (b) at least one array comprising M cameras, where M is a positive integer; (c) optional optical markers and means for attaching the optical markers to at least one surgical tool; and (d) a computerized algorithm operable via the controller, the computerized algorithm adapted to record images received by each camera of each of the M cameras and to calculate therefrom the position of each of the tools, and further adapted to provide automatically the results of the calculation to the human operator of the interface.

[0480] It is well known that surgery is a highly dynamic procedure with a constantly changing environment which depends on many variables. A non-limiting list of these variables includes, for example: the type of the surgery, the working space (e.g., with foreign objects, dynamic uncorrelated movements, etc), the type of tools used during the surgery, changing background, relative movements, dynamic procedures, dynamic input from the operator and the history of the patient. Therefore, there is need for a system which is able to integrate all the variables by weighting their importance and deciding to which spatial position the endoscope should be relocated.

[0481] The present invention can be also utilized to improve the interface between the operators (e.g., the surgeon, the operating medical assistant, the surgeon's colleagues, etc.). Moreover, the present invention can be also utilized to control and/or direct an automated maneuvering subsystem to focus the endoscope on an instrument selected by the surgeon, or to any other region of interest. This may be performed in order to estimate the location of at least one surgical tool during a surgical procedure.

[0482] The present invention also discloses a surgical tracking system which is adapted to guide and relocate an endoscope to a predetermined region of interest in an automatic and/or a semi-automatic manner. This operation is assisted by an image processing algorithm(s) which is adapted to analyze the received data from the endoscope in real time, and to assess the surgical environment of the endoscope.

[0483] According to an embodiment, the system comprises a "smart" tracking subsystem, which receives instructions from a maneuvering function f(t) (t is the time) as to where to direct the endoscope and which instructs the maneuvering subsystem to relocate the endoscope to the required area.

[0484] The maneuvering function f(t) receives, as input, output from at least two instructing functions $g_i(t)$, analyses their output and provides instruction to the "smart" tracking system (which eventually re-directs the endoscope).

[0485] According to some embodiments, each instructing function $g_i(t)$ is also given a weighting function, $\alpha_i(t)$.

[0486] The instructing functions $g_i(t)$ of the present invention are functions which are configured to assess the environment of the endoscope and the surgery, and to output data which guides the tracking subsystem for controlling the spatial position of the maneuvering subsystem and the endoscope. The instructing functions $g_i(t)$ may be selected from a group consisting of:

- **[0487]** a. a tool detection function $g_1(t)$;
- **[0488]** b. a movement detection function $g_2(t)$;
- **[0489]** c. an organ detection function $g_3(t)$;
- **[0490]** d. a collision detection function $g_4(t)$;
- **[0491]** e. an operator input function $g_5(t)$;
- **[0492]** f. a prediction function $g_6(t)$;
- **[0493]** g. a past statistical analysis function $g_7(t)$;
- **[0494]** h. a most used tool function $g_8(t)$;
- **[0495]** i. a right tool function $g_9(t)$;
- **[0496]** j. a left tool function $g_{10}(t)$;
- **[0497]** k. a field of view function $g_{11}(t)$;
- **[0498]** l. a preferred volume zone function $g_{12}(t)$;
- **[0499]** m. a no fly zone function $g_{13}(t)$;
- **[0500]** n. a proximity function $g_{14}(t)$;
- **[0501]** o. a tagged tool function $g_{15}(t)$;
- **[0502]** p. a preferred tool function $g_{16}(t)$.

[0503] Thus, for example, the maneuvering function f(t) receives input from two instructing functions: the collision detection function $g_4(t)$ (the function providing information whether the distance between two elements is smaller than a predetermined distance) and from the most used tool function $g_8(t)$ (the function counts the number of times each tool is moved during a surgical procedure and provides information as to whether the most moved or most used tool is currently moving). The output given from the collision detection function $g_4(t)$ is that a surgical tool is dangerously close to an organ in the surgical environment. The output given from the most used tool function $g_8(t)$ is that the tool identified statistically as the most moved tool is currently moving.

[0504] The maneuvering function f(t) then assigns each of the instructing functions with weighting functions $\alpha_i(t)$. For example, the most used tool function $g_8(t)$ is assigned with a greater weight than the weight assigned to the collision detection function $g_4(t)$.

[0505] After the maneuvering function f(t) analyses the information received from the instructing functions $g_i(t)$ and the weighting functions $\alpha_i(t)$ of each, the same outputs instructions to the maneuvering subsystem to re-direct the endoscope (either to focus on the moving tool or on the tool approaching dangerously close to the organ).

[0506] It should be emphasized that all of the above (and the following disclosure) is enabled by constantly monitoring and locating/identifying the 3D spatial location of each element/tool in the surgical environment.

[0507] The identification is provided by conventional means known to any skilled in the art (e.g., image processing, optical means etc.).

[0508] According to some embodiments, the surgical tracking subsystem comprises:

- **[0509]** a. at least one endoscope adapted to acquire real-time images of a surgical environment within the human body;
- **[0510]** b. a maneuvering subsystem adapted to control the spatial position of the endoscope during the laparoscopic surgery; and,
- **[0511]** c. a tracking subsystem in communication with the maneuvering subsystem, adapted to control the maneuvering subsystem so as to direct and modify the spatial position of the endoscope to a region of interest.

[0512] According to this embodiment, the tracking subsystem comprises a data processor. The data processor is adapted to perform real-time image processing of the surgical environment and to instruct the maneuvering subsystem to modify the spatial position of the endoscope according to input received from a maneuvering function f(t); the maneuvering function f(t) is adapted to (a) receive input from at least two instructing functions $g_i(t)$, where i is 1, . . . , n and n≥2 and where t is time; i and n are integers; and (b) to output instructions to the maneuvering subsystem based on the input from the at least two instructing functions $g_i(t)$, so as to spatially position the endoscope to the region of interest.

[0513] According to one embodiment, the tool detection function $g_1(t)$ is adapted to detect tools in the surgical environment. According to this embodiment, the tool detection function is adapted to detect surgical tools in the surgical environment and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the detected surgical tools.

[0514] According to some embodiments, the functions $g_i(t)$ may rank the different detected areas in the surgical environment according to a ranking scale (e.g., from 1 to 10) in which prohibited areas (i.e., areas which are defined as area to which the surgical tools are forbidden to 'enter) receive the lowest score (e.g., 1) and preferred areas (i.e., areas which are defined as area in which the surgical tools should be maintained) receive the highest score (e.g., 10).

[0515] According to a preferred embodiment, one function $g_1(t)$ is adapted to detect tools in the surgical environment and inform the maneuvering function f(t) if they are in preferred areas or in prohibited areas.

[0516] According to some embodiments, the movement detection function $g_2(t)$ comprises a communicable database comprising the real-time 3D spatial positions of each of the surgical tools in the surgical environment; means to detect movement of the at least one surgical tool when a change in the 3D spatial positions is received, and means to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the moved surgical tool.

[0517] According to some embodiments, the organ detection function $g_3(t)$ is adapted to detect physiological organs in the surgical environment and to classify the detected organs as prohibited areas or preferred areas. For example, if the operator instructs the system that the specific surgery is kidney surgery, the organ detection function $g_3(t)$ will classify the kidneys (or one kidney, if the surgery is specified to be on a single kidney) as a preferred area and other organs will be classified as prohibited areas. According to another embodiment, the organ detection function is adapted to detect organs in the surgical environment and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the detected organs. According to some embodiments, the right tool function is adapted to detect surgical tool positioned to right of the endoscope and to output instructions to the tracking subsystem to instruct the maneuvering system to constantly direct the endoscope on the right tool and to track the right tool.

[0518] According to another embodiment, the left tool function is adapted to detect surgical tool positioned to left of the endoscope and to output instructions to the tracking subsystem to instruct the maneuvering system to constantly direct the endoscope on the left tool and to track the left tool.

[0519] According to some embodiments, the collision detection function $g_4(t)$ is adapted to detect prohibited areas within the surgical environment so as to prevent collisions between the endoscope and the prohibited areas. For example, if the endoscope is located in a narrow area in which a precise movement of the same is preferred, the collision detection function $g_4(t)$ will detect and classify different areas (e.g., nerves, veins, walls of organs) as prohibited areas. Thus, according to this embodiment, the collision prevention function is adapted to define a predetermined distance between the at least one surgical tool and an anatomical element within the surgical environment; and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the surgical tool and the anatomical element within the surgical environment if the distance between the at least one surgical tool and an anatomical element is less than the predetermined distance. According to one embodiment of the present invention the anatomical element is selected from a group consisting of tissue, organ, another surgical tool and any combination thereof.

[0520] According to some embodiments, the operator input function $g_5(t)$ is adapted to receive an input from the operator. The input can be, for example: an input regarding prohibited areas in the surgical environment, an input regarding allowed areas in the surgical environment, or an input regarding the region of interest and any combination thereof. The operator input function $g_5(t)$ can receive instructions from the operator before or during the surgery, and respond accordingly.

[0521] According to some embodiments, the operator input function may further comprise a selection algorithm for selection of areas selected from a group consisting of: prohibited areas, allowed areas, regions of interest, and any combination thereof. The selection may be performed via an input device (e.g., a touch screen).

[0522] According to some embodiments, the operator input function $g_5(t)$ comprises a communicable database; the communicable database is adapted to receive an input from the operator of the system; the input comprising n 3D spatial positions; n is an integer greater than or equal to 2; and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the at least one 3D spatial position received.

[0523] According to some embodiments, the prediction function $g_6(t)$ is adapted to provide data regarding a surgical environment at a time $t_f>t_0$, wherein t_0 is the present time and t_f is a future time. The prediction function $g_6(t)$ may communicate with a database which stores data regarding the environment of the surgery (e.g., the organs in the environment). This data may be used by the prediction function $g_6(t)$ for the prediction of expected or unexpected events or expected or unexpected objects during the operation. Thus, according to this embodiment, the prediction function $g_6(t)$ comprises a communicable database storing each 3D spatial position of each of surgical tool within the surgical environment, such that each movement of each surgical tool is stored; the prediction function is adapted to (a) to predict the future 3D spatial position of each of the surgical tools (or each object); and, (b) to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the future 3D spatial position.

[0524] According to some embodiments, the past statistical analysis function $g_7(t)$ is adapted to provide data regarding the surgical environment or the laparoscopic surgery based on past statistical data stored in a database. The data regarding the surgical environment may be for example: data regarding prohibited areas, data regarding allowed areas, data regarding the region of interest and any combination thereof. Thus, according to this embodiment, the past statistical analysis function $g_6(t)$ comprises a communicable database storing each 3D spatial position of each of surgical tool within the surgical environment, such that each movement of each surgical tool is stored; the past statistical analysis function $g_6(t)$ is adapted to (a) perform statistical analysis on the 3D spatial positions of each of the surgical tools in the past; and, (b) to predict the future 3D spatial position of each of the surgical tools; and, (c) to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the future 3D spatial position. Thus, according to the past statistical analysis function $g_7(t)$, the past movements of each tool are analyzed and, according to this analysis, a prediction of the tool's next move is provided.

[0525] According to another embodiment, the most used tool function $g_8(t)$ comprises a communicable database counting the amount of movement of each surgical tool located within the surgical environment; the most used tool function is adapted to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to constantly position the endoscope to track the movement of the most moved surgical tool. The amount of movement of a tool can be defined as the total number of movements of that tool or the total distance the tool has moved.

[0526] According to some embodiments, the right tool function $g_9(t)$ is adapted to detect at least one surgical tool in a specified position in relation to the endoscope, preferably positioned to right of the endoscope and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to constantly direct the endoscope to the right tool and to track the same. According to preferred embodiments, the right tool is defined as the tool positioned to the right of the endoscope; according to other embodiments, any tool can be defined as the right tool.

[0527] According to another embodiment, the left tool function $g_{10}(t)$ is adapted to detect at least one surgical tool in a specified position in relation to the endoscope, preferably positioned to left of the endoscope and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to constantly direct the endoscope to the left tool and to track the same. According to preferred embodiments, the left tool is defined as the tool positioned to the left of the endoscope; according to other embodiments, any tool can be defined as the left tool.

[0528] According to another embodiment, the field of view function $g_{11}(t)$ comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the combination of all of the n 3D spatial positions provides a predetermined field of view; the field of view function is adapted to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to at least one 3D spatial position substantially within the n 3D spatial positions so as to maintain a constant field of view.

[0529] According to another embodiment, the preferred volume zone function $g_{12}(t)$ comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the n 3D spatial positions provide the preferred volume zone; the preferred volume zone function $g_{12}(t)$ is adapted to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to at least one 3D spatial position substantially within the preferred volume zone.

[0530] According to another embodiment, the no fly zone function $g_{13}(t)$ comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the n 3D spatial positions define a predetermined volume within the surgical environment; the no fly zone function $g_{13}(t)$ is adapted to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to at least one 3D spatial position substantially different from all the n 3D spatial positions.

[0531] According to some embodiments, the proximity function $g_{14}(t)$ is adapted to define a predetermined distance between at least two surgical tools; and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the two surgical tools if the distance between the two surgical tools is less than or if it is greater than the predetermined distance.

[0532] According to another embodiment, the proximity function $g_{14}(t)$ is adapted to define a predetermined angle between at least three surgical tools; and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the three surgical tools if the angle between the two surgical tools is less than or if it is greater than the predetermined angle.

[0533] According to another embodiment, the preferred volume zone function comprises communicable database comprising n 3D spatial positions; n is an integer greater than or equals to 2; the n 3D spatial positions provides the preferred volume zone; the preferred volume zone function is adapted to output instructions to the tracking subsystem to instruct the maneuvering system to direct the endoscope to the preferred volume zone.

[0534] According to another embodiment, the field of view function comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equals to 2; the combination of all of the n 3D spatial positions provides a predetermined field of view; the field of view function is adapted to output instructions to the tracking subsystem to instruct the maneuvering system to direct the endoscope to at least one 3D spatial position substantially within the n 3D spatial positions so as to maintain a constant field of view.

[0535] According to another embodiment, the no fly zone function comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equals to 2; the n 3D spatial positions define a predetermined volume within the surgical environment; the no fly zone function is adapted to output instructions to the tracking subsystem to instruct the maneuvering system to direct the endoscope to at least one 3D spatial position substantially different from all the n 3D spatial positions.

[0536] According to another embodiment, the most used tool function comprises a communicable database counting the amount of movement of each surgical tool located within the surgical environment; the most used tool function is adapted to output instructions to the tracking subsystem to instruct the maneuvering system to direct the endoscope to constantly position the endoscope to track the movement of the most moved surgical tool.

[0537] According to some embodiments, the prediction function $g_6(t)$ is adapted to provide data regarding a surgical environment in a time $t_f > t$, wherein t is the present time and t_f is the future time. The prediction function $g_6(t)$ may communicate with a database which stores data regarding the environment of the surgery (e.g., the organs in the environment). This data may be used by the prediction function $g_6(t)$ for the prediction of expected or unexpected events or object during the operation. Thus, according to this embodiment, the prediction function comprises a communicable database storing each 3D spatial position of each of surgical tool within the surgical environment, such that each movement of each surgical tool is stored; the prediction function is adapted to (a) to predict the future 3D spatial position of each of the surgical tools; and, (b) to output instructions to the tracking subsystem to instruct the maneuvering system to direct the endoscope to the future 3D spatial position.

[0538] According to some embodiments, the past statistical analysis function $g_7(t)$ is adapted to provide data regarding the surgical environment or the laparoscopic surgery based on past statistical data stored in a database. The data regarding the surgical environment may be for example: data regarding prohibited areas, data regarding allowed areas, data regarding the region of interest. Thus, according to this embodiment, the past statistical analysis function comprises a communicable database storing each 3D spatial position of each of surgical tool within the surgical environment, such that each movement of each surgical tool is stored; the past statistical analysis function is adapted to (a) statistical analyze the 3D spatial positions of each of the surgical tools in the past; and, (b) to predict the future 3D spatial position of each of the surgical tools; and, (c) to output instructions to the tracking subsystem to instruct the maneuvering system to direct the endoscope to the future 3D spatial position. Thus, according to the past statistical analysis function $g_7(t)$, the past movements of each tool are analyzed and according to this analysis a future prediction of the tool's next move is provided.

[0539] According to some embodiments, preferred tool function comprises a communicable database, the database stores a preferred tool; the preferred tool function is adapted to output instructions to the tracking subsystem to instruct the maneuvering system to constantly direct the endoscope to the preferred tool, such that said endoscope constantly tracks said preferred tool.

[0540] Thus, according to the preferred tool function the endoscope constantly tracks the preferred tool, such that the field of view, as seen from the endoscope, is constantly maintained on said preferred tool. It should be noted that the user may define in said preferred tool function to constantly track the tip of said preferred tool or alternatively, the user may define in said preferred tool function to constantly track the body or any location on the preferred tool.

[0541] According to some embodiments, the tagged tool function $g_{15}(t)$ comprises means adapted to tag at least one surgical tool within the surgical environment and to output instructions to the tracking subsystem to instruct the maneuvering subsystem to constantly direct the endoscope to the tagged surgical tool. Thus, according to the tagged tool function, the endoscope constantly tracks the preferred (i.e., tagged) tool, such that the field of view, as seen from the endoscope, is constantly maintained on the preferred (tagged) tool. It should be noted that the user can define the tagged tool function to constantly track the tip of the preferred (tagged) tool, the body of the preferred (tagged) tool, or any other location on the preferred (tagged) tool.

[0542] According to some embodiments, the means are adapted to constantly tag at least one surgical tool within the surgical environment.

[0543] According to some embodiments, the preferred tool function $g_{16}(t)$ comprises a communicable database. The database stores a preferred tool; and the preferred tool function is adapted to output instructions to the tracking subsystem to instruct the maneuvering subsystem to direct the endoscope to the preferred tool.

[0544] According to some embodiments, the system further comprises means adapted to re-tag the at least one of the surgical tools until a desired tool is selected.

[0545] According to some embodiments, the system further comprises means adapted to toggle the surgical tools. According to some embodiments, the toggling is performed manually or automatically.

[0546] According to different embodiments of the present invention, the weighting functions $\alpha_i(t)$ are time-varying functions (or constants), the value of which is determined by the operator or the output of the instructing functions $g_i(t)$. For example, if a specific function $g_i(t)$ detected an important event or object, its weighting functions $\alpha_i(t)$ may be adjusted in order to elevate the chances that the maneuvering function f(t) will instruct the maneuvering subsystem to move the endoscope towards this important event or object.

[0547] According to different embodiments of the present invention, the tracking subsystem may implement various image processing algorithms which may also be algorithms that are well known in the art. The image processing algorithms may be for example: image stabilization algorithms, image improvement algorithms, image compilation algorithms, image enhancement algorithms, image detection algorithms, image classification algorithms, image correlations with the cardiac cycle or the respiratory cycle of the human body, smoke reduction algorithms, vapor reduction algorithms, steam reduction algorithms and any combination thereof. Smoke, vapor and steam reduction algorithms may be needed as it is known that, under certain conditions, smoke, vapor or steam may be emitted by or from the endoscope. The image processing algorithm may also be implemented and used to analyze 2D or 3D representations which may be rendered from the real-time images of the surgical environment.

[0548] According to different embodiments, the endoscope may comprise an image acquisition device selected from a group consisting of: a camera, a video camera, an electromagnetic sensor, a computer tomography imaging device, a fluoroscopic imaging device, an ultrasound imaging device, and any combination thereof.

[0549] According to some embodiments, the system may also comprise a display adapted to provide input or output to the operator regarding the operation of the system. The display may be used to output the acquired real-time images of a surgical environment with augmented reality elements. The display may also be used for the definition of the region of interest by the operator.

[0550] According to some embodiments, the endoscope may be controlled be an endoscope controller for performing operations such as: acquiring the real-time images and zooming-in to a predetermined area. For example, the endoscope controller may cause the endoscope to acquire the real-time images in correlation with the cardiac cycle or the respiratory cycle of a human body.

[0551] According to different embodiments, the data processor of the present invention may operate a pattern recognition algorithm for assisting the operation of the instructing functions $g_i(t)$. The pattern recognition algorithm may be used as part of the image processing algorithm.

[0552] It should be emphasized that all of the above (and the following disclosure) is enabled by constantly monitoring and locating/identifying the 3D spatial location of each element/tool in the surgical environment.

[0553] The identification is provided by conventional means known to any skilled in the art (e.g., image processing, optical means etc.).

[0554] It should be emphasized that all of the above (and the following disclosure) is enabled by constantly monitoring and locating/identifying the 3D spatial location of each element/tool in the surgical environment.

[0555] The identification is provided by conventional means known to any skilled in the art (e.g., image processing, optical means etc.).

[0556] Reference is made now to FIG. **27**, which is a general schematic view of an embodiment of a surgical tracking system **100**. In this figure are illustrated surgical instruments **17***b* and **17***c* and an endoscope **21** which may be maneuvered by means of maneuvering subsystem **19** according to the instructions received from a tracking subsystem operable by computer **15**.

[0557] According to one embodiment of the present invention as defined in the above, the user may define the field of view function as constantly monitoring at least one of surgical instruments **17***b* and **17***c*.

[0558] According to this embodiment, the surgical tracking system **100** may also comprise one or more button operated wireless transmitters **12***a*, which transmit, upon activation, a single code wave **14** through aerial **13** to connected receiver **11** that produces a signal processed by computer **15**, thereby directing and modifying the spatial position of endoscope **21** to the region of interest, as defined by the field of view function.

[0559] Alternatively, according to the proximity rule, if the distance between the surgical instruments **17***b* and **17***c* is smaller than a predetermined distance (as defined by the collision prevention rule), the system alerts the user that any movement of either one of the surgical instruments **17***b* and **17***c* that will reduce the distance is a RESTRICTED movement.

[0560] In preferred embodiments of the present system, the system comprises all the mechanisms required to control fully the movement of an articulated endoscope so that the position and angle of the tip of the endoscope are fully under control. Such control is preferably automatic, as described herein, but it can be manual and controlled by a joystick or other control under the command of a surgeon.

[0561] In some embodiments, a standard articulating endoscope, such as the Stryker™ articulating endoscope is used. In other embodiments, an integral articulating endoscope is used.

[0562] FIGS. **28***a-b* show an embodiment wherein the fine control means is a control mechanism (**1830**) which attaches to the endoscope (**1810**). The fine control mechanism attaches to the manual controls (**1820**) for the articulating endoscope via a connector (**1840**). In a preferred embodiment, the connector can connect any endoscope control means with any articulating endoscope. FIG. **28***a* shows the fine control mechanism (**1830**) before it is attached to the articulating endoscope (**1810**), while FIG. **28***b* shows the control mechanism (**1830**) attached to the articulating endoscope (**1810**), with the endoscope manual control (**1840**) connected to the fine control mechanism via the connector (**1830**).

[0563] In some embodiments, such as that shown in FIG. **28**, hardware control of the articulation is used, with the current system in effect replacing the surgeon by moving the controls of the articulating tool. In other embodiments, software control is used, with the current system in effect replacing the controls of the articulating tool so that the tool articulates based on commands coming directly from the current system rather than via the tool's manual controls.

[0564] FIG. **29** shows an embodiment of the articulating endoscope (**1810**) in use. The endoscope (**1810**) is attached to the zoom mechanism of the coarse control system (**1960**), which is attached to the articulating arm (**1970**) of the coarse control system. The fine control mechanism (**1830**) is attached to the articulating endoscope (**1810**) and also enabled to be controlled (either in a wired manner or wirelessly) either automatically by the control system or manually by the endoscope operator. The fine control mechanism (**1840**) is also connected to the manual controls (**1922**, **1924**) of the articulating endoscope. In this example, one control (**1922**) is forward and one (**1924**) is backward, turning the endoscope tip (**1950**) toward the right of the figure.

[0565] FIG. **30***a-d* shows articulation of an embodiment of the articulating endoscope. FIG. **30***a* illustrates the flexibility of the articulating tip, showing it in typical positions—bent forwards, out of the plane of the paper (**1952**), to the right (**1954**), downward (**1956**), and to the left and backward, into the plane of the paper (**1958**).

[0566] FIGS. **30***b-d* illustrate the articulating tip (**1950**) in use, following the movements of the tip (**2082**) of a medical instrument (**2080**). In FIG. **30***b*, the endoscope tip (**1950**) is straight; it is not yet following the tip of the instrument (**2082**). In FIG. **30***c*, the instrument tip (**2082**) has moved to the right and the tip of the endoscope (**1950**) has turned right to follow the tip (**2082**) of the instrument. It can be seen from the angle of the endoscope (**1950**) that the pivoting point of the endoscope has not changed, although the field of view of the endoscope (**1950**) has changed significantly. In FIG. **30***d*, the instrument tip (**2082**) has moved towards the endocope and forward, out of the plane of the paper. The tip of the endoscope (**1950**) has rotated to follow the movement of the instrument tip (**2082**), but the pivoting point of the endoscope has not changed. It is clear from FIGS. **30***a-d* that use of the articulating endoscope allows the surgeon a much larger field of view than would be possible with only movement of an endoscope around the pivoting point. Use of an articulating endoscope also minimizes movement of the whole endoscope relative to the pivoting point, which has the possibility of causing unwanted movement of the pivoting point and, therefore, unwanted movement of the field of view.

EXAMPLES

[0567] Examples are given in order to prove the embodiments claimed in the present invention. The example, which is a clinical test, describes the manner and process of the present invention and set forth the best mode contemplated by the inventors for carrying out the invention, but are not to be construed as limiting the invention.

[0568] In the examples below, similar numbers refer to similar parts in all of the figures.

[0569] In FIGS. **31-44** in the examples below, for simplicity and clarity, a rigid tool has been illustrated although the rules are equally applicable to both rigid and articulating tools.

Example 1

Tracking System with Collision Avoidance System

[0570] One embodiment of such a rule-based system will comprise the following set of commands:

[0571] Detection (denoted by Gd):

[0572] Gd1 Tool location detection function

[0573] Gd2 Organ (e.g. Liver) detection function

[0574] Gd3 Movement (vector) calculation and estimation function

[0575] Gd4 Collision probability detection function

[0576] Tool Instructions (denoted Gt):

[0577] Gt1 Move according to manual command

[0578] Gt2 Stop movement

[0579] The scenario—manual move command by the surgeon:

[0580] Locations Gd1 (t) and Gd2(t) are calculated in real time at each time step (from an image or location marker).

[0581] Tool movement vector Gd3(t) is calculated from Gd1(t) as the difference between the current location and at least one previous location (probably also taking into account previous movement vectors).

[0582] The probability of collision—Gd4(t)—is calculated, for example, from the difference between location Gd1 and location Gd2 (the smaller the distance, the closer the proximity and the higher the probability of collision), from movement vector Gd3(t) indicating a collision, etc.

Tool Instructions $Gt1$ Weight function $\alpha_1(t)=1$ If $Gt1(t)<$a predetermined threshold and 0 otherwise

Tool Instructions $Gt2$ Weight function $\alpha_2(t)=1$ If $Gt2(t)>$a predetermined threshold and 0 otherwise

Tool Instructions$=\alpha_1(t)*Gt1+\alpha_2(t)*Gt2(t)$;

[0583] In reference to FIG. **31**, which shows, in a non-limiting manner, an embodiment of a tracking system and collision avoidance system. The system tracks a tool **310** and the liver **320**, in order to determine whether a collision between the tool **310** and the liver **320** is possible within the next time step. FIGS. **31***a* and **31***b* show how the behavior of the system depends on the distance **330** between the tool **310** and the liver **320**, while FIGS. **31***c* and **31***d* show how movement of the tool **310** affects the behavior. In FIG. **31***a*, the distance **330** between the tool **310** and the liver **320** is large enough that a collision is not possible in that time step. Since no collision is possible, no movement of the tool is commanded. In FIG. **31***b*, the distance **330** between the tool **310** and the liver **320** is small enough that a collision is likely. In the embodiment illustrated, a movement **340** is commanded to move the tool **310** away from the liver **320**. In other embodiments, the system prevents movement **350**, but does not command movement **340**; in such embodiments, the tool **310** will remain close to the liver **320**. In yet other embodiments, the system warns/signals the operator that the move is RESTRICTED, but does not restrict movement **350** or command movement **340** away from the liver. Such a warning/signaling can be visual or aural, using any of the methods known in the art.

[0584] FIGS. **31***c* and **31***d* illustrate schematically the effect of the movement of tool **310** on the collision avoidance system. In FIGS. **31***c* and **31***d*, the tool **310** is close enough to the liver **320** that a collision between the two is possible. If the system tracked only the positions of the tool **310** and the liver **320**, then motion of the tool **310** away from the liver **320** would be commanded. FIG. **31***c* illustrates the effect of a movement **350** that would increase the distance between tool **310** and liver **320**. Since the movement **350** is away from liver **320**, no collision is possible in this time step and no movement of the tool **310** is commanded.

[0585] In FIG. **31***d*, tool **310** is the same distance from liver **320** as in FIG. **31***c*. However, in FIG. **31***d*, the movement **350** of the tool **310** is toward the liver **320**, making a collision between tool **310** and liver **320** possible. In some embodiments, a movement **340** is commanded to move the tool **310** away from the liver **320**. In other embodiments, the system prevents movement **350**, but does not command movement **340**; in this embodiment the tool **310** will remain close to the liver **320**. In yet other embodiments, the system warns the operator that move is RESTRICTED, but does not restrict movement **350** or command movement **340** away from the liver. Such a warning can be visual or aural, using any of the methods known in the art.

[0586] As a non-limiting example, in an operation on the liver, the collision detection function can warn the operator that a collision between a tool and the liver is likely but not prevent the collision. In an operation on the gall bladder, the collision detection function can prevent a collision between the tool and the liver, either by preventing the movement or by commanding a movement redirecting the tool away from the liver,

Example 2

Tracking System with Soft Control—Fast Movement when Nothing is Nearby, Slow Movement when Something is Close

[0587] One embodiment of such rule-based system comprises the following set of commands:

[0588] Detection (denoted by Gd):

[0589] Main Tool location detection function (denoted by GdM);

[0590] Gd-tool1-K—Tool location detection function;

[0591] Gd-organ2-L—Organ (e.g. Liver) detection function;

[0592] Gd3 Main Tool Movement (vector) calculation and estimation function;

[0593] Gd4 Proximity probability detection function;

[0594] Tool Instructions (denoted Gt):

[0595] Gt1 Movement vector (direction and speed) according to manual command

[0596] The scenario—manual move command by the surgeon:

[0597] Locations GdM(t), Gd-tool1-K(t) and Gd-organ2-L (t) are calculated in real time at each time step (from image or location marker).

[0598] Main Tool Movement Vector Gd3(t) is calculated per GdM (t) as the difference between the current location and at least one previous location (probably also taking into account previous movement vectors)

[0599] The proximity of the main tool to other tools—Gd4 (t)—is calculated, for example, as the smallest of the differences between the main tool location and the other tools' locations.

[0600] Tool Instructions Gt1 Weight function $\alpha_1(t)$ is proportional to tool proximity function Gd4(t), the closer the tool the slower the movement so that, for example

$$\alpha_2(t)=Gd4/\text{maximum}(Gd4)$$

or

$$\alpha_2(t)=\log(Gd4/\text{maximum}(Gd4))$$ where maximum ($Gd4$) is the maximum distance which is likely to result in a collision given the distances, the speed of the tool and the movement vector.

$$\text{Tool Instructions}=\alpha_1(t)*Gt1.$$

Example 3

Tracking System with No-Fly Rule/Function

[0601] In reference to FIG. **32***a*-*d*, which shows, in a non-limiting manner, an embodiment of a tracking system with no-fly rule. The system tracks a tool **310** with respect to a no-fly zone (**460**), in order to determine whether the tool will enter the no-fly zone (**460**) within the next time step. In this example, the no-fly zone **460** surrounds the liver.

[0602] FIGS. **32***a* and **32***b* show how the behavior of the system depends on the location of the tool tip with respect to the no-fly zone, while FIGS. **32***c* and **32***d* show how movement of the tool affects the behavior.

[0603] In FIG. **32***a*, the tool **310** is outside the no-fly zone rule/function **460** and no movement of the tool is commanded. In FIG. **32***b*, the tool **310** is inside the no-fly zone **460**.

[0604] The no-fly zone rule/function performs as follows:

[0605] In the embodiment illustrated, a movement **350** is commanded to move the tool **310** away from the no-fly zone **460**. In other embodiments, the system prevents movement further into the no-fly zone (refers as movement **340**, see FIG. **32***c*), but does not command movement **340**; in such embodiments, the tool **310** will remain close to the no-fly zone **460**.

[0606] In yet other embodiments, the system warns/signals the operator that the move is RESTRICTED, but does not restrict movement further into the no-fly zone or command movement **340** away from the no-fly zone **460**. Such a warning/signaling can be visual or aural, using any of the methods known in the art.

[0607] FIGS. **32***c* and **32***d* illustrate schematically the effect of the tool's movement on operation of the no-fly zone rule/function. In FIGS. **32***c* and **32***d*, the tool **310** is close enough to the no-fly zone **460** (distance **330** is small enough) that it is possible for the tool to enter the no-fly zone during the next time step. FIG. **32***c* illustrates the effect of a movement **340** that would increase the distance between tool **310** and no-fly zone **460**. Since the movement **340** is away from no-fly zone **460**, no collision is possible in this time step and no movement of the tool **310** is commanded.

[0608] In FIG. **32***d*, tool **310** is the same distance from no-fly zone **460** as in FIG. **32***c*. However, in FIG. **32***d*, the movement **340** of the tool is toward no-fly zone **460**, making it possible for tool **310** to enter no-fly zone **460**. In the embodiment illustrated, a movement **350** is commanded to move the tool **310** away from the no-fly zone **460**. In other embodiments, the system prevents movement **340**, but does not command movement **350**; in such embodiments, the tool **310** will remain close to the no-fly zone **460**. In yet other embodiments, the system warns/signals the operator that the move is RESTRICTED, but does not restrict movement **340** or command movement **350** away from the no-fly zone rule/function **460**. Such a warning/signaling can be visual or aural, using any of the methods known in the art.

Example 4

Tracking System with Preferred Volume Zone Rule/Function

[0609] In reference to FIG. **33***a*-*d*, which shows, in a non-limiting manner, an embodiment of a tracking system with a preferred volume zone function/rule.

[0610] The system tracks a tool **310** with respect to a preferred volume zone (**570**), in order to determine whether the tool will leave the preferred volume (**570**) within the next time step.

[0611] In this example, the preferred volume zone **570** extends over the right lobe of the liver. FIGS. **33***a* and **33***b* show how the behavior of the system depends on the location of the tool tip with respect to the preferred volume zone **570**, while FIGS. **33***c* and **33***d* show how movement of the tool affects the behavior (i.e., the preferred volume zone rule/function).

[0612] In FIG. **33***a*, the tool **310** is inside the preferred volume zone **570** and no movement of the tool is commanded. In FIG. **33***b*, the tool **310** is outside the preferred volume zone **570**.

[0613] In the embodiment illustrated, a movement **340** is commanded to move the tool **310** away from the preferred volume zone **570**. In other embodiments, the system prevents movement **340**; in such embodiments, the tool **310** will remain close to the preferred volume zone **570**. In yet other embodiments, the system warns/signals the operator that the move **340** is RESTRICTED. Such a warning/signaling can be visual or aural, using any of the methods known in the art.

[0614] FIGS. **33***c* and **33***d* illustrate schematically the effect of the tool's movement on operation of the preferred volume rule/function. In FIGS. **33***c* and **33***d*, the tool **310** is close enough to the edge of preferred volume zone **570** that it is possible for the tool to leave the preferred volume zone during the next time step.

[0615] FIG. **33***c* illustrates the effect of a movement **350** that would take the tool **310** deeper into preferred volume zone **570**. Since the movement **350** is into preferred volume **570**, said movement is an allowed movement.

[0616] In FIG. **33***d*, the movement **350** of the tool is out of the preferred volume **570**, making it possible for tool **310** to leave preferred volume **570**.

[0617] According to one embodiment illustrated, a movement **340** is commanded to move the tool **310** into the preferred volume zone **570**. In other embodiments, the system prevents movement **350**, but does not command movement **340**; in such embodiments, the tool **310** will remain close to the preferred volume zone **570**. In yet other embodiments, the system warns/signals the operator that the move is RESTRICTED, but does not restrict movement **350** or command movement **340** away from the preferred volume zone **570**. Such a warning/signaling can be visual or aural, using any of the methods known in the art.

Example 5

Organ/Tool Detection Function

[0618] In reference to FIG. **34**, which shows, in a non-limiting manner, an embodiment of an organ detection system (however, it should be noted that the same is provided for detection of tools, instead of organs).

[0619] For each organ, the 3D spatial positions of the organs stored in a database. In FIG. **34**, the perimeter of each organ is marked, to indicate the edge of the volume of 3D spatial locations stored in the database.

[0620] In FIG. **34**, the liver **610** is labeled with a dashed line. The stomach **620** is labeled with a long-dashed line, the intestine **630** with a solid line and the gall bladder **640** is labeled with a dotted line.

[0621] In some embodiments, a label or tag visible to the operator is also presented. Any method of displaying identifying markers known in the art can be used. For non-limiting example, in an enhanced display, colored or patterned markers can indicate the locations of the organs, with the marker either indicating the perimeter of the organ or the area of the display in which it appears.

Example 6

Tool Detection Function

[0622] In reference to FIG. **35**, which shows, in a non-limiting manner, an embodiment of a tool detection function. For each tool, the 3D spatial positions of the tools stored in a database. In FIG. **35**, the perimeter of each tool is marked, to indicate the edge of the volume of 3D spatial locations stored in the database. In FIG. **35**, the left tool is labeled with a dashed line while the right tool is labeled with a dotted line.

[0623] In some embodiments, a label or tag visible to the operator is also presented. Any method of displaying identifying markers known in the art can be used. For non-limiting example, in an enhanced display, colored or patterned markers can indicate the locations of the tools, with the marker either indicating the perimeter of the tool or the area of the display in which it appears.

Example 7

Movement Detection Function/Rule

[0624] In reference to FIG. **36***a-b*, which shows, in a non-limiting manner, an embodiment of a movement detection function/rule. FIG. **36***a* schematically illustrates a liver **810**, a left tool **820** and a right tool **830** at a time t. FIG. **36***b* schematically illustrates the liver **810**, left tool **820** and right tool **830** at a later time t+Δt, where Δt is a small time interval. In this example, the left tool **820** has moved downward (towards the direction of liver **810**) in the time interval Δt.

[0625] The system has detected movement of left tool **820** and labels it. This is illustrated schematically in FIG. **36***b* by a dashed line around left tool **820**.

Example 8

Prediction Function

[0626] In reference to FIG. **37***a-d*, which shows, in a non-limiting manner, an embodiment of the above discussed prediction function.

[0627] FIG. **37***a* shows a left tool **920** and a right tool **930** at a time t.

[0628] FIG. **37***b* shows the same tools at a later time t+Δt, where Δt is a small time interval. Left tool **920** is moving to the right and downward, while right tool **930** is moving to the left and upward. If the motion continues (shown by the dashed line in FIG. **37***c*), then by the end of the next time interval, in other words, at some time between time t+Δt and time t+2Δt, the tools will collide, as shown by tool tips within the dotted circle **950** in FIG. **37***c*.

[0629] In this embodiment, the system automatically prevents predicted collisions and, in this example, the system applies a motion **940** to redirect left tool **920** so as to prevent the collision.

[0630] In other embodiments, the system warns/signals the operator that a collision is likely to occur, but does not alter the movement of any tool. Such a warning/signaling can be visual or aural, using any of the methods known in the art.

[0631] In other embodiments, the prediction function can be enabled to, for non-limiting example, alter the field of view to follow the predicted movement of a tool or of an organ, to warn of (or prevent) predicted motion into a no-fly zone, to warn of (or prevent) predicted motion out of a preferred zone.

Example 9

Right Tool Function/Rule

[0632] In reference to FIG. **38**, which shows, in a non-limiting manner, an embodiment of a right tool function. FIG. **38** schematically illustrates a liver **1010**, a left tool **1020** and a right tool **1030**.

[0633] The right tool, illustrated schematically by the dashed line **1040**, is labeled and its 3D spacial location is constantly and real-time stored in a database. Now, according to the right tool function/rule the endoscope constantly tracks the right tool.

[0634] It should be pointed out that the same rule/function applies for the left tool (the left tool function/rule).

Example 10

Field of View Function/Rule

[0635] In reference to FIG. **39***a-b*, which shows, in a non-limiting manner, an embodiment of a field of view function/rule.

[0636] FIG. **39***a* schematically illustrates a field of view of the abdomen at a time t. In the field of view are the liver **1110**, stomach **1120**, intestines **1130** and gall bladder **1140**.

[0637] The gall bladder is nearly completely visible at the left of the field of view. Two tools are also in the field of view, with their tips in proximity with the liver. These are left tool **1150** and right tool **1160**. In this example, the field of view function/rule tracks left tool **1150**. In this example, left tool **1150** is moving to the right, as indicated by arrow **1170**.

[0638] FIG. **39***b* shows the field of view at time t+Δt. The field of view has moved to the right so that the tip of left tool **1150** is still nearly at the center of the field of view. It can be seen that much less of gall bladder **1140** is visible, while more of right tool **1160** has entered the field of view.

[0639] The field of view function/rule can be set to follow a selected tool, as in this example or to keep a selected organ in the center of the field of view. It can also be set to keep a particular set of tools in the field of view, zooming in or out as necessary to prevent any of the chosen tools from being outside the field of view.

[0640] Alternatively, the field of view function/rule defines n 3D spatial positions; n is an integer greater than or equal to 2; the combination of all of said n 3D spatial positions provides a predetermined field of view.

[0641] Each movement of the endoscope or the surgical tool within said n 3D spatial positions is an allowed movement and any movement of the endoscope or the surgical tool outside said n 3D spatial positions is a restricted movement.

[0642] Alternatively, said the field of view function/rule defines n 3D spatial positions; n is an integer greater than or equal to 2; the combination of all of said n 3D spatial positions provides a predetermined field of view.

[0643] According to the field of view function/rule, the endoscope is relocated if movement has been detected by said detection means, such that said field of view is maintained.

Example 11

Tagged Tool Function/Rule (or Alternatively the Preferred Tool Rule)

[0644] In reference to FIG. **40**, which shows, in a non-limiting manner, an embodiment of a tagged tool function/rule.

[0645] FIG. **40** shows three tools (**1220**, **1230** and **1240**) in proximity to the organ of interest, in this example, the liver **1210**.

[0646] The tool most of interest to the surgeon, at this point during the operation, is tool **1240**. Tool **1240** has been tagged (dotted line **1250**); the 3D spatial location of tool **1240** is constantly stored in a database and this spatial location has been labeled as one of interest.

[0647] The system can use this tagging for many purposes, including, but not limited to, keeping tool **1240** in the center of the field of view, predicting its future motion, keeping it from colliding with other tools or keeping other tools from colliding with it, instructing the endoscope to constantly monitor and track said tagged tool **1250** and so on.

[0648] It should be noted that in the preferred tool rule, the system tags one of the tools and performs as in the tagged tool rule/function.

Example 12

Proximity Function/Rule

[0649] In reference to FIG. **41***a-c*, which shows, in a non-limiting manner, an embodiment of a proximity function/rule.

[0650] FIG. **41***a* schematically illustrates two tools (**1310** and **1320**) separated by a distance **1330** which is greater than a predefined proximity distance. Since tool **1310** is not within proximity of tool **1320**, the field of view (**1380**) does not move.

[0651] FIG. **41***b* schematically illustrates two tools (**1310** and **1320**) separated by a distance **1330** which is less than a predefined proximity distance.

[0652] Since tool **1310** is within proximity of tool **1320**, the field of view **1380** moves upward, illustrated schematically by arrow **1340**, until the tips of tool **1310** and tool **1320** are in the center of field of view **1380** (FIG. **41***c*).

[0653] Alternatively the once the distance **1330** between the two tool **1320** and **1310** is smaller than a predetermined distance, the system alerts the user of said proximity (which might lead to a collision between the two tools). Alternatively, the system moves one of the tools away from the other one.

Example 13

Operator Input Function/Rule

[0654] In reference to FIG. **42***a-b*, which shows, in a non-limiting manner, an embodiment of an operator input function/rule. According to this embodiment, input is received from the operator.

[0655] In the following example, the input received from the operator is which tool to track.

[0656] FIG. **42***a* schematically illustrates an endoscope with field of view **1480** showing a liver **1410** and two tools **1420** and **1430**. Operator **1450** first selects the tip of the left tool as the region of interest, preferably by touching the tool tip on the screen, causing the system to tag (**1440**) the tip of the left tool.

[0657] As illustrated in FIG. **42***b*, the system then directs and modifies the spatial position of the endoscope so that the tagged tool tip **1440** is in the center of the field of view **1480**.

[0658] Another example of the operator input function/rule is the following:

[0659] If a tool has been moved closely to an organ in the surgical environment, according to the proximity rule or the collision prevention rule, the system will, according to one embodiment, prevent the movement of the surgical tool.

[0660] According to one embodiment of the present invention, once the surgical tool has been stopped, any movement of said tool in the direction is interpreted as input from the operator to continue the movement of said surgical tool in said direction.

[0661] Thus, according to this embodiment, the operator input function/rule receives input from the operator (i.e., physician) to continue the move of said surgical tool (even though it is “against” the collision prevention rule). Said input is simply in the form of the continued movement of the surgical tool (after the alert of the system or after the movement prevention by the system).

Example 14

Constant Field of View Rule/Function

[0662] In reference to FIGS. **43***a-d*, which shows, in a non-limiting manner, an embodiment of a tracking system with a constant field of view rule/function.

[0663] In many endoscopic systems, the tip lens in the camera optics is not at a right angle to the sides of the endoscope. Conventionally, the tip lens angle is described relative to the right angle, so that a tip lens at right angles to the sides of the endoscope is described as having an angle of 0. Typically, angled endoscope tip lenses have an angle of 30° or 45°. This tip lens angle affects the image seen during zooming. FIG. **43** illustrates, in an out-of-scale manner, for a conventional system, the effect of zooming in the field of view in an endoscope with tip lens set straight in the end (FIGS. **43***a* and **43***b*) vs. the effect of zooming in the field of view in an endoscope with angled tip lens (FIGS. **43***c* and **43***d*).

[0664] FIGS. **43***a* and **43***c* illustrate the endoscope (**100**), the object it is viewing (**200**) and the image seen by the endoscope camera (**130**) before the zoom. The solid arrows (**160**) show the limits of the FOV and the dashed arrow (**170**), the center of the field of view (FOV); since the object is in the center of the FOV, an image of the object (**210**) is in the center of the camera image (**130**). FIGS. **43***b* and **43***d* illustrate the endoscope (**100**), the object it is viewing (**200**) and the image seen by the endoscope camera (**130**) after the zoom. The solid arrows (**160**) show the limits of the FOV and the dashed arrow (**170**), the center of the field of view.

[0665] If the tip lens is set straight in the end of the endoscope (FIGS. **43***a* and **43***b*), an object (**200**) in the center of the field of view will be in the center of the field of view (FOV) (and the camera image) (**130**) both before (FIG. **43***a*) and after (FIG. **43***b*) the zoom. However, if the tip lens is set at an angle in the end of the endoscope (FIGS. **43***c* and **43***d*), then an object that is in the center of the FOV (and the camera image) before the zoom (FIG. **43***c*) will not be in the center of the FOV (or the camera image) after the zoom (FIG. **43***d*) since the direction of motion of the endoscope is not the direction in which the center of the field of view (**170**) points.

[0666] In an embodiment of the system of the present invention, unlike in conventional systems, the controlling means maintains the center of the field of view (FOV) during zoom independent of the tip lens angle. An advantage of controlling the zoom of the endoscope via a data processing system is that the tip lens angle does not need to be input to the data processing system, obviating a possible source of error.

[0667] According to one embodiment of the present invention, the endoscope's movement will be adjusted in order to maintain a constant field of view.

Example 15

Misalignment Rule/Function

[0668] According to another embodiment of the present invention, the system can inform the user of any misalignment of the same system.

[0669] Misalignment of the system may cause parasitic movement of the endoscope tip, where the endoscope tip does not move exactly in the expected direction. According to one embodiment of the system, the system comprises sensors (e.g., gyroscopes, accelerometers and any combination thereof) that calculate/estimates the position of the pivot point in real time in order to (a) inform the user of misalignment; or (b) calculate the misalignment so that the system can adjust its movement to prevent parasitic movement.

Example 16

Change of Speed Rule/Function

[0670] In reference to FIG. **44**, which shows, in a non-limiting manner, an embodiment of a tracking system with a change of speed rule/function.

[0671] In conventional endoscopic control systems, motion of the endoscope occurs at a single speed. This speed is fairly fast so that the endoscope can be moved rapidly between locations that are well separated. However, this means that making fine adjustments so difficult that fine adjustments are normally not made. In an embodiment of the present invention, the speed of the tip of the endoscope is automatically varied such that, the closer the endoscope tip is to an object, be it a tool, an obstacle, or the object of interest, the more slowly it moves. In this embodiment, as shown in FIG. **44**, measurements are made of the distance X (**150**) from the tip (**195**) of the endoscope (**100**) to the pivot point of the endoscope (**190**), where said pivot point is at or near the surface of the skin (**1100**) of a patient (**1000**). Measurements are also made of the distance Y (**250**) from the tip of the endoscope (**195**) to the object in the center of the scene of view (**200**). From a predetermined velocity V_p, the actual velocity of the tip of the endoscope at a given time, V_{act}, is calculated from

$$V_{act} \propto \frac{Y}{X} V_p$$

[0672] Therefore, the closer to the object at the center of the scene of view, the more slowly the endoscope moves, making it possible to use automatic control of even fine adjustments, and reducing the probability that the endoscope will come in contact with tissue or instruments.

Example 17

Articulation of Tool

[0673] In reference to FIG. **45***a-b*, a non-limiting example of movement of an articulating tool (**310**), here an endoscope, is shown schematically.

[0674] In FIG. **45***a-b*, the endoscope (**310**) is moved so that, instead of viewing the outer side of the liver (**320**) from the right, it views the inner side of the liver (**320**) from the left.

[0675] FIG. **45***a* shows the endoscope (**310**) at the beginning of the movement. It is fully extended and its tip (**318**) is positioned about halfway up the outer side of the liver. The dashed line shows the movement of the base (**312**) of the endoscope, which will move in a straight line from its starting position (FIG. **45***a*) to its final position (FIG. **45***b*). The dotted line shows the movement of the endoscope tip (**318**)—the tip (**318**) moves upward, over the top of the liver (**320**), and then down the inner side of the liver (**320**), to allow imaging of the left (inner) side of the liver from between the liver (**320**) and the lungs (**1790**).

[0676] In FIG. **45***b*, the movement has been completed. The endoscope tip (**318**) now points rightward; the articulating section (**316**) being curved so that the endoscope (**310**) views the right side of the liver (**310**), with the endoscope tip (**318**) being between the liver (**320**) and the lungs (**1790**) while its base (**312**) remains on the right side of the body.

Example 18

Articulation of Tool

[0677] In reference to FIG. **46**, a non-limiting example of flexion of an articulating tool (**310**), here an endoscope, is shown schematically.

[0678] In FIG. **46**, portions of the small intestine (**1795**) are shown schematically. The endoscope enters the body from the body's right side (body not shown), and views a portion of the small intestine (**1795**F) from the left and below. The articulating section of the endoscope (**316**) bypasses a loop of small intestine (**1795**A), passes between two portions of small intestine (**1795**B, **1795**C), and over other portions of small intestine (**1795**D, **1795**E) so that the endoscope's tip (**318**) views the desired portion of the small intestine (**1795**F) from the desired direction.

[0679] In the foregoing description, embodiments of the invention, including preferred embodiments, have been presented for the purpose of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise form disclosed. Obvious modifications or variations are possible in light of the above teachings. The embodiments were chosen and described to provide the best illustration of the principals of the invention and its practical application, and to enable one of ordinary skill in the art to utilize the invention in various embodiments and with various modifications as are suited to the particular use contemplated. All such modifications and variations are within the scope of the invention as determined by the appended claims when interpreted in accordance with the breadth they are fairly, legally, and equitably entitled.

What is claimed is:

1. A surgical controlling system, comprising:

a. at least one surgical tool configured by means of shape and size to be inserted into a surgical environment of a human body for assisting a surgical procedure, at least one said surgical tool being an articulating tool

b. at least one location estimating means configured to real-time locate the 3D spatial position of said at least one surgical tool at any given time t;

c. at least one movement detection means communicable with a movement's database and with said location estimating means; said movement's database is configured to store said 3D spatial position of said at least one surgical tool at time t_f and at time t_0, where $t_f > t_0$; said movement detection means is configured to detect movement of said at least one surgical tool if the 3D spatial position of said at least one surgical tool at time t_f is different than said 3D spatial position of said at least one surgical tool at time t_O; and,

d. a controller having a processing means communicable with a controller's database, said controller configured, to control the spatial position of said at least one surgical tool; said controller's database is in communication with said movement detection means; said controller comprising instructions configured, when executed, for moving said at least one surgical tool;

wherein said controller is configured to change the articulation of said articulating tool during said direction of said surgical tool to said location via said instructions provided by said controller.

2. The system of claim **1**, wherein either: (a) said system additionally comprises an endoscope; (b) at least one of said surgical tools is an endoscope; and said system comprises:

a. at least one lens at the distal end of said endoscope, said lens characterized by a field of view;

b. at least one camera located in a proximal end of said endoscope, configured to real-time provide at least one 2D image of at least a portion of said surgical environment by means of said at least one lens;

c. at least one light source, configured to real-time illuminate at least a portion of said at least one object within at least a portion of said field of view with at least one time and space varying predetermined light pattern, said predetermined light pattern is a structured light pattern;

d. at least one sensor configured to detect light reflected from said field of view;

e. a computer program which, when executed by data processing apparatus, is configured to generate a 3D image of said field of view; said 3D image constructable from said detected light reflected from said field of view and said structured light pattern.

3. The system of claim **2**, wherein said construction of said 3D image is by means of calculating the world coordinates of at least one point on said at least one object; at least one of the following being held true:

a. said world coordinates of at least one point on said at least one object calculateable from the following equation:

$$\tilde{\alpha} = \frac{n^T \tilde{x}_p}{n^T R_p v_c}.$$

where n^T is the transpose of the normal to the plane defined by the stripe id x_p, $\tilde{x}_p = x_p + [\delta x_p, 0, f_p]^T$ is the perturbed stripe id x_p, R_p is the rotation matrix defining the transformation between the world coordinate system and the projector coordinate system and v_c is the direction of the ray between the stripe id and the object point;

b. for any point X_w in world coordinate system, the coordinate X_c of the same point in the camera coordinate system is calculated according to the following equation:

$$X_c = C_c X_w,$$

where C_c, the camera perspective projection matrix, is of the form

$$C_c = \alpha \begin{bmatrix} f_x & kf_y & x_c^0 \\ 0 & f_y & y_c^0 \\ 0 & 0 & 1 \end{bmatrix} [R_c \quad t_c]$$

where α is a proportion coefficient, f_x and f_y are the camera focal length scaled to each of the camera image dimensions, k is the shear of the camera coordinate system, x_c^0 and y_c^0 are the origin of X_c in image coordinates, and R_c and t_c define the transformation between the world coordinate system and the light source's coordinate system, with R_c being a rotation matrix and t_c a translation matrix;

c. x_p^0 is the x-coordinate of the intersection of the optical axis and the projector;

d. for any point X_w in world coordinate system, the coordinate X_p of the same point in the light source coordinate system is calculated according to the following equation:

$$X_p = C_p X_w,$$

where C_p, the light source perspective projection matrix, is of the form

$$C_p = \alpha \begin{bmatrix} f_p & 0 & x_p^0 \\ 0 & 0 & 1 \end{bmatrix} [R_p \quad t_p]$$

where α is a proportion coefficient, f_p is the light source focal length scaled to projector dimensions, x_p^0 is the origin of X_p in projector coordinates, and R_p and t_p define the transformation between the world coordinate system and the light source's coordinate system, with R_p being a rotation matrix and t_p a translation matrix;

e. the world coordinates p_w of a point P is calculated according to the following equation:

$$\begin{pmatrix} p_p \\ p_s \end{pmatrix} - \begin{pmatrix} F_c(p_w;\Theta_c) \\ F_p(p_w;\Theta_p) \end{pmatrix} = 0$$

where $p_p=(x_p,y_p)^t$ is the pixel coordinate of said point, $p_x=(x_s)$ is the stripe value of said point P, $F_c(P_w;\Theta_c)=P_p-\epsilon_p$ is the noise-free value of the vector of pixel coordinates, where P_p is the vector of measured pixel coordinates and ϵ_p is the vector of errors in the pixel coordinates; $F_p(P_w;\Theta_p)=P_s-\epsilon_s$ is the noise-free value of the vector of stripe coordinates, where P_s is the vector of measured stripe coordinates and ϵ_s is the vector of errors in the stripe coordinates;

f. x_p^0 is the x-coordinate of the intersection of the optical axis and the projector;

g. the world coordinates p_w of a point P is estimated according to the following non-linear least squares (NLLS) equations:

$$\min_{\Theta_c} \|P_p - F_c(P_w;\Theta_c)\|^2$$

$$\min_{\Theta_p} \|P_s - F_p(P_w;\Theta_p)\|^2$$

h. x_p^0 is the x-coordinate of the intersection of the optical axis and the projector;

i. said NLLS equations are solvable by means of a NLLS solving algorithm selected from a group consisting of the Gauss-Newton technique, the quasi-Newton technique, and the Levenberg-Marquardt technique; and

j. the location, in world coordinates, of a kth point on the object is calculated according to the following equation:

$$p_w^k = \frac{C_{1,2,1}^k - x_p C_{3,2,1}^k - y_p C_{1,3,1}^k - x_s C_{1,2,2}^k + x_s x_p C_{3,2,2}^k + x_x y_p C_{1,3,2}^k}{C_{1,2,1}^4 - x_p C_{3,2,1}^4 - y_p C_{1,3,1}^4 - x_s C_{1,2,2}^4 + x_s x_p C_{3,2,2}^4 + x_x y_p C_{1,3,2}^4}$$

where ${C_{i,j,l}}^k=\det({C_c}^i,{C_c}^j,{C_p}^l,e_k)$ are constants which depend only on a camera perspective transformation matrix and a projector perspective transformation matrix.

4. The system of claim **2**, additionally comprising a calibration object, at least one of the following being held true:

a. said calibration object is of predetermined shape and size; and

b. said calibration object comprises fiducial locations of predetermined position.

5. The system of claim **2**, wherein at least one of the following is held true:

a. said lens is a wide-angle lens, said wide-angle lens is selected from a group consisting of a fisheye lens, an omnidirectional lens and any combination thereof;

b. at least one said surgical tool comprises at least one proximity sensor positioned on the outer circumference of the same;

c. said structured light uses at least one of a group consisting of: temporal sequencing, spatial sequencing, wavelength sequencing and any combination thereof;

d. the relationship between the location of a point in said camera image, the location of a point in a light source and the location of a point in space is known for all said points in said camera image, said points in said light source and said points in space; said 3D image being generatable from said known relationships and said 2D camera image; and

6. The system of claim **1**, additionally comprising a touchscreen; said location within said surgical environment of said human body is determinable from pressure on a portion of said touchscreen; at least one of the following being held true:

a. said portion of said touchscreen is that which displays the image of said location; and

b. said portion of said touchscreen displays a direction indicator, said direction indicator selected from a group consisting of: an arrow pointing in a predefined direction, a line pointing in a predefined direction, a pointer pointing in a predefined direction, the word "left", the word "right" the word "up", the word "down", the word "forward", the word "back", the word "zoom", the word "in", the word "out", and any combination thereof.

7. The system of claim **1**, wherein said instructions comprise a predetermined set of rules selected from a group consisting of: most used tool rule, right tool rule, left tool rule, field of view rule, no fly zone rule, a route rule, environmental rule, operator input rule, proximity rule; collision prevention rule, history-based rule, tool-dependent ALLOWED and RESTRICTED movements rule, preferred volume zone rule, preferred tool rule, movement detection rule, tagged tool rule, change of speed rule and any combination thereof, at least one of the following being held true:

a. said route rule comprises a communicable database storing predefined route in which said at least one surgical tool is configured to move within said surgical environment; said predefined route comprises n 3D spatial positions of said at least one surgical tool; n is an integer greater than or equal to 2; said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said n 3D spatial positions of said predefined route, and said RESTRICTED movements are movements in which said location of said at least one surgical tool is substantially different from said n 3D spatial positions of said predefined route;

b. said environmental rule comprises a comprises a communicable database; said communicable database configured to receive at least one real-time image of said surgical environment and comprises instructions configured, when executed, to perform real-time image processing of the same and to determine the 3D spatial position of hazards or obstacles in said surgical environment; said environmental rule is configured to determine said ALLOWED and RESTRICTED movements according to said hazards or obstacles in said surgical environment, such that said RESTRICTED movements are movements in which said at least one surgical tool is located substantially in at least one of said 3D spatial positions, and said ALLOWED movements are movements in which the location of said at least one surgical tool is substantially different from said 3D spatial positions;

c. said operator input rule comprises a communicable database; said communicable database is configured to receive an input from the operator of said system regarding said ALLOWED and RESTRICTED movements of said at least one surgical tool;

d. said proximity rule is configured to define a predetermined distance between at least two surgical tools; said ALLOWED movements are movements which are within the range or out of the range of said predetermined distance, and said RESTRICTED movements are movements which are out of the range or within the range of said predetermined distance;

e. said proximity rule is configured to define a predetermined angle between at least three surgical tools; said ALLOWED movements are movements which are within the range or out of the range of said predetermined angle, and said RESTRICTED movements which are out of the range or within the range of said predetermined angle;

f. said collision prevention rule is configured to define a predetermined distance between said at least one surgical tool and an anatomical element within said surgical environment; said ALLOWED movements are movements which are in a range that is larger than said predetermined distance, and said RESTRICTED movements are movements which is in a range that is smaller than said predetermined distance;

g. said history-based rule comprises a communicable database storing each 3D spatial position of each said surgical tool, such that each movement of each surgical tool is stored; said history-based rule is configured to determine said ALLOWED and RESTRICTED movements according to historical movements of said at least one surgical tool, such that said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said 3D spatial positions, and said RESTRICTED movements are movements in which the location of said at least one surgical tool is substantially different from said n 3D spatial positions;

h. said tool-dependent ALLOWED and RESTRICTED movements rule comprises a communicable database storing predetermined characteristics of at least one said surgical tool; such that said ALLOWED and RESTRICTED movements are determinable according to said predetermined characteristics of said surgical tool; and ALLOWED movements are movements of said endoscope which track said surgical tool having said predetermined characteristics; and

i. said system further comprises a maneuvering subsystem communicable with said controller, said maneuvering subsystem is configured to spatially reposition said at least one surgical tool during a surgery according to said predetermined set of rules, such that if said movement of said at least one surgical tool is a RESTRICTED movement, said maneuvering subsystem prevents said movement,

8. The system of claim **1**, wherein at least one of the following is true:

a. said hazards or obstacles in said surgical environment are selected from a group consisting of tissue, a surgical tool, an organ, an endoscope and any combination thereof;

b. said input comprises n 3D spatial positions; n is an integer greater than or equal to 2; wherein at least one of which is defined as ALLOWED location and at least one of which is defined as RESTRICTED location, such that said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said at least one surgical tool is substantially different from said n 3D spatial positions;

c. said input comprises at least one rule according to which ALLOWED and RESTRICTED movements of said at least one surgical tool are determined, such that the spatial position of said at least one surgical tool is controlled by said controller according to said ALLOWED and RESTRICTED movements;

d. said operator input rule converts an ALLOWED movement to a RESTRICTED movement and a RESTRICTED movement to an ALLOWED movement; cc

e. said anatomical element is selected from a group consisting of tissue, organ, another surgical tool and any combination thereof;

f. said right tool rule is configured to determine said ALLOWED movement of said endoscope according to the movement of the surgical tool positioned to right of said endoscope; further wherein said left tool rule is configured to determine said ALLOWED movement of said endoscope according to the movement of the surgical tool positioned to left of said endoscope;

g. said tagged tool rule comprises means configured to tag at least one surgical tool within said surgical environment and to determine said ALLOWED movement of said endoscope so as to constantly track the movement of said tagged surgical tool;

h. said field of view rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; the combination of all of said n 3D spatial positions provides a predetermined field of view; said field of view rule is configured to determine said ALLOWED movement of said endoscope within said n 3D spatial positions so as to maintain a constant field of view, such that said ALLOWED movements are movements in which said endoscope is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said endoscope is substantially different from said n 3D spatial positions;

i. said preferred volume zone rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; said n 3D spatial positions provides said preferred volume zone; said preferred volume zone rule is configured to determine said ALLOWED movement of said endoscope within said n 3D spatial positions and RESTRICTED movement of said endoscope outside said n 3D spatial positions, such that said ALLOWED movements are movements in which said endoscope is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said endoscope is substantially different from said n 3D spatial positions;

j. said preferred tool rule comprises a communicable database, said database stores a preferred tool; said preferred tool rule is configured to determine said ALLOWED movement of said endoscope to constantly track the movement of said preferred tool;

k. said no fly zone rule comprises a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; said n 3D spatial positions define a predetermined volume within said surgical environment; said no fly zone rule is configured to determine said RESTRICTED movement if said movement is within said no fly zone and ALLOWED movement if said movement is outside said no fly zone, such that said RESTRICTED movements are movements in which said at least one of said surgical tool is located substantially in at least one of said n 3D spatial positions, and said ALLOWED movements are movements in which the location of said at least one endoscope is substantially different from said n 3D spatial positions;

l. said most used tool rule comprises a communicable database counting the amount of movement of each said surgical tool; said most used tool rule is configured to constantly position said endoscope to track the movement of the most moved surgical tool; said system further comprises a maneuvering subsystem communicable with said controller, said maneuvering subsystem is configured to spatially reposition said at least one surgical tool during a surgery according to said predetermined set of rules; further wherein said system is configured to alert the physician of said RESTRICTED movement of said at least one surgical tool;

m. said alert is selected from a group consisting of audio signaling, voice signaling, light signaling, flashing signaling and any combination thereof;

n. said ALLOWED movement is permitted by said controller and said RESTRICTED movement is denied by said controller;

o. said tool-dependent ALLOWED and RESTRICTED movements rule comprises a communicable database; said communicable database is configured to store predetermined characteristics of at least one of said surgical tool; said tool-dependent ALLOWED and RESTRICTED movements rule is configured to determine said ALLOWED and RESTRICTED movements according to said predetermined characteristics of said surgical tool; such that ALLOWED movements are movements of said endoscope which track said surgical tool having said predetermined characteristics; and

p. said movement detection rule comprises a communicable database comprising the real-time 3D spatial positions of each said surgical tool; said movement detection rule is configured to detect movement of said at least one surgical tool when a change in said 3D spatial positions is received, such that said ALLOWED movements are movements in which said endoscope is re-directed to focus on said moving surgical tool.

9. The system of claim **1**, wherein at least one of the following is being held true:

a. said at least one location estimating means comprises at least one endoscope configured to acquire real-time images of said surgical environment within said human body; and at least one surgical instrument spatial location software configured, when executed, to receive said real-time images of said surgical environment and to estimate said 3D spatial position of said at least one surgical tool;

b. said at least one location estimating means comprises (a) at least one element selected from a group consisting of optical imaging means, radio frequency transmitting and receiving means, at least one mark on said at least one surgical tool and any combination thereof; and, (b) at least one surgical instrument spatial location software configured to estimate said 3D spatial position of said at least one surgical tool by means of said element;

c. said at least one location estimating means is an interface subsystem between a surgeon and said at least one surgical tool, the interface subsystem comprising:

  i. at least one array comprising N regular or pattern light sources, where N is a positive integer;

  ii. at least one array comprising M cameras, where M is a positive integer;

  iii. optional optical markers and means for attaching the optical marker to the at least one surgical tool; and;

  iv. a computerized algorithm operable via the controller, the computerized algorithm configured, when executed, to record images received by each camera of each of the M cameras and to calculate therefrom the position of each of the tools, and further configured to provide automatically the results of the calculation to the human operator of the interface; and

d. said predetermined characteristics of said surgical tool are selected from a group consisting of: physical dimensions, structure, weight, sharpness, and any combination thereof.

10. The system of claim **1**, wherein at least one of the following is held true:

a. said articulating tool has articulations substantially at the tip of said tool, substantially along the body of said too, and any combination thereof;

b. control of articulation is selected from a group consisting of hardware control, software control and any combination thereof and

c. said tool has articulation in a regions selected from a group consisting of near the tip of said tool, on the body of said tool, and any combination thereof.

11. A method of using a structured-light based surgical controlling system, comprising steps of:

a. providing a surgical controlling system comprising:

  i. at least one surgical tool configured to be inserted into a surgical environment of a human body for assisting a surgical procedure, at least one said surgical tool being an articulating tool;

  ii. at least one location estimating means configured to real-time locate the 3D spatial position of said at least one surgical tool at any given time t;

  iii. at least one movement detection means communicable with a movement's database and with said location estimating means; said movement's database is configured to store said 3D spatial position of said at least one surgical tool at time t_f and at time t_0, where $t_f > t_0$; said movement detection means is configured to detect movement of said at least one surgical tool if the 3D spatial position of said at least one surgical tool at time t_f is different than said 3D spatial position of said at least one surgical tool at time t_O; and,

  iv. a controller having a processing means communicable with a controller's database, said controller configured to control the spatial position of said at least one surgical tool; said controller's database is in communication with said movement detection means; and

v. at least one touchscreen configured to display an image of at least a portion of said surgical environment of said human body and to receive input of at least one location within said surgical environment of said human body;

b. inserting at least one said surgical tool into said surgical environment;

c. displaying said 3D image of said field of view via said touchscreen;

d. determining said location within said surgical environment of said human body from pressure on a portion of said touchscreen;

e. estimating the 3D spatial position of at least one said surgical tool; and

f. directing and moving said surgical tool to said location via instructions provided by said controller.

12. The method of claim **11**, additionally comprising steps of:

a. either (i) selecting at least one said tool to be an endoscope; or (ii) selecting at least one of said surgical tools to be an endoscope;

b. providing said system with:

i. at least one lens at said endoscope's distal end;

ii. at least one camera located in said endoscope's proximal end, configured to real-time provide at least one 2D image of at least a portion of said field of view by means of said at least one lens;

iii. at least one light source, configured to real-time illuminate at least a portion of said at least one object within at least a portion of said field of view with at least one time and space varying predetermined light pattern;

iv. at least one sensor configured to detect light reflected from said field of view;

v. a computer program which, when executed by data processing apparatus, is configured to generate a 3D image of said field of view;

c. maneuvering said endoscope and controlling the movements of the same;

d. illuminating said at least a portion of said field of view with said at least one time and space varying predetermined light pattern; said predetermined light pattern being a structured light pattern;

e. detecting said light reflected from said field of view;

f. generating, from said detected light reflected from said field of view and said structured light pattern, said 3D image of said field of view;

13. The method of claim **12**, additionally comprising step of constructing said 3D image by calculating the world coordinates of at least one point on said at least one object further comprising at least one of the following steps:

a. calculating said world coordinates of said at least one point on said at least one object from the following equation:

$$\tilde{\alpha} = \frac{n^T \tilde{x}_p}{n^T R_p v_c}.$$

where n^T is the transpose of the normal to the plane defined by the stripe id x_p, $\tilde{x}_p = x_p + [\delta x_p, 0, f_p]^T$ is the perturbed stripe id x_p, R_p is the rotation matrix defining the transformation between the world coordinate system and the projector coordinate system and v_c is the direction of the ray between the stripe id and the object point.

b. for any point X_w in world coordinate system, calculating the coordinate X_c of the same point in the camera coordinate system according to the following equation:

$$X_c = C_c X_w,$$

where C_c, the camera perspective projection matrix, is of the form

$$C_c = \alpha \begin{bmatrix} f_x & kf_y & x_c^0 \\ 0 & f_y & y_c^0 \\ 0 & 0 & 1 \end{bmatrix} [\, R_c \quad t_c \,].$$

where α is a proportion coefficient, f_x and f_y are the camera focal length scaled to each of the camera image dimensions, k is the shear of the camera coordinate system, x_c^0 and y_c^0 are the origin of X_c in image coordinates, and R_c and t_c define the transformation between the world coordinate system and the light source's coordinate system, with R_c being a rotation matrix and t_c a translation matrix.

c. of defining x_p^0 to be the x-coordinate of the intersection of the optical axis and the projector.

d. for any point X_w in world coordinate system, calculating the coordinate X_p of the same point in the light source coordinate system according to the following equation:

$$X_p = C_p X_w,$$

where C_p, the light source perspective projection matrix, is of the form

$$C_p = \alpha \begin{bmatrix} f_p & 0 & x_p^0 \\ 0 & 0 & 1 \end{bmatrix} [\, R_p \quad t_p \,]$$

where α is a proportion coefficient, f_p is the light source focal length scaled to projector dimensions, x_p^0 is the origin of X_p in projector coordinates, and R_p and t_p define the transformation between the world coordinate system and the light source's coordinate system, with R_p being a rotation matrix and t_p a translation matrix.

e. calculating the world coordinates of a point P according to the following equation:

$$\begin{pmatrix} p_p \\ p_s \end{pmatrix} - \begin{pmatrix} F_c(p_w; \Theta_c) \\ F_p(p_w; \Theta_p) \end{pmatrix} = 0$$

where $p_p = (x_p, y_p)^t$ is the pixel coordinate of said point, $p_x = (x_s)$ is the stripe value of said point P, $F_c(P_w; \Theta_c) = P_p - \epsilon_p$ is the noise-free value of the vector of pixel coordinates, where P_p is the vector of measured pixel coordinates and ϵ_p is the vector of errors in the pixel coordinates; $F_p(P_w; \Theta_p) = P_s - \epsilon_s$ is the noise-free value of the vector of stripe coordinates, where P_s is the vector of measured stripe coordinates and ϵ_s is the vector of errors in the stripe coordinates.

f. estimating the world coordinates p_w of a point P according to the following non-linear least squares (NLLS) equations:

$$\min_{\Theta_c} \|P_p - F_c(P_w; \Theta_c)\|^2$$

$$\min_{\Theta_p} \|P_s - F_p(P_w; \Theta_p)\|^2$$

g. solving said NLLS equations using a NLLS solving algorithm selected from a group consisting of the Gauss-Newton technique, the quasi-Newton technique, and the Levenberg-Marquardt technique.

h. calculating the location, in world coordinates, of a kth point on the object according to the following equation:

$$p_w^k = \frac{C_{1,2,1}^k - x_p C_{3,2,1}^k - y_p C_{1,3,1}^k - x_s C_{1,2,2}^k + x_s x_p C_{3,2,2}^k + x_x y_p C_{1,3,2}^k}{C_{1,2,1}^4 - x_p C_{3,2,1}^4 - y_p C_{1,3,1}^4 - x_s C_{1,2,2}^4 + x_s x_p C_{3,2,2}^4 + x_x y_p C_{1,3,2}^4}$$

where $C_{i,j,l}{}^k = \det(C_c{}^i, C_c{}^j, C_p{}^l, e_k)$ are constants which depend only on a camera perspective transformation matrix and a projector perspective transformation matrix.

14. The method of claim **11**, additionally comprising step of providing a calibration object and further comprising at least one of the following steps:

a. providing said calibration object of a predetermined shape and size

b. providing said calibration object comprising fiducial marks at predetermined positions.

15. The method of claim **11**, additionally comprising at least one of the following steps:

a. selecting said lens to be a wide-angle lens and of selecting said wide-angle lens from a group consisting of a fisheye lens, an omnidirectional lens and any combination thereof;

b. positioning at least one proximity sensor on the outer circumference of at least one said tool;

c. using at least one of a group consisting of: temporal sequencing, spatial sequencing, wavelength sequencing and any combination thereof in said structured light pattern; and

d. determining the relationship between the location of a point in said camera image, the location of a point in a light source and the location of a point in space for all said points in said camera image, said points in said light source and said points in space and of using said known relationships to generate said 3D image from said 2D camera image.

16. The method of claim **11**, additionally comprising at least one of the following steps:

a. selecting said portion of said touchscreen to be that which displays the image of said location.

b. displaying a direction indicator on said portion of said touchscreen, said direction indicator selected from a group consisting of: an arrow pointing in a predefined direction, a line pointing in a predefined direction, a pointer pointing in a predefined direction, the word "left", the word "right" the word "up", the word "down", the word "forward", the word "back", the word "zoom", the word "in", the word "out", and any combination thereof.

17. The method of claim **11**, additionally comprising steps of selecting said instructions from a predetermined set of rules selected from a group consisting of: most used tool rule, right tool rule, left tool rule, field of view rule, no fly zone rule, a route rule, environmental rule, operator input rule, proximity rule; collision prevention rule, history-based rule, tool-dependent ALLOWED and RESTRICTED movements rule, preferred volume zone rule, preferred tool rule, movement detection rule, tagged tool rule, change of speed rule and any combination thereof, and further comprising:

a. said route rule comprises steps of: providing a communicable database; storing a predefined route in which said at least one surgical tool is configured to move within said surgical environment; comprising said predefined route of n 3D spatial positions of said at least one surgical tool, n is an integer greater than or equal to 2; said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said n 3D spatial positions of said predefined route, and said RESTRICTED movements are movements in which said location of said at least one surgical tool is substantially different from said n 3D spatial positions of said predefined route.

b. said environmental rule comprises steps of: providing a communicable database; receiving at least one real-time image of said surgical environment in said communicable database; performing real-time image processing of the same and determining the 3D spatial position of hazards or obstacles in said surgical environment; determining said ALLOWED and RESTRICTED movements according to said hazards or obstacles in said surgical environment, such that said RESTRICTED movements are movements in which said at least one surgical tool is located substantially in at least one of said 3D spatial positions, and said ALLOWED movements are movements in which the location of said at least one surgical tool is substantially different from said 3D spatial positions.

c. said operator input rule comprises steps of: providing a communicable database; and receiving input from an operator of said system regarding said ALLOWED and RESTRICTED movements of said at least one surgical tool.

d. said proximity rule comprises steps of: defining a predetermined distance between at least two surgical tools; said ALLOWED movements are movements which are within the range or out of the range of said predetermined distance, and said RESTRICTED movements are movements which are out of the range or within the range of said predetermined distance.

e. said proximity rule comprises steps of: defining a predetermined angle between at least three surgical tools; said ALLOWED movements are movements which are within the range or out of the range of said predetermined angle, and said RESTRICTED movements are movements which are out of the range or within the range of said predetermined angle.

f. said collision prevention rule comprises steps of: defining a predetermined distance between said at least one surgical tool and an anatomical element within said surgical environment; said ALLOWED movements are movements which are in a range that is larger than said predetermined distance, and said RESTRICTED movements are movements which is in a range that is smaller than said predetermined distance.

g. said history-based rule comprises steps of: providing a communicable database storing each 3D spatial position of each said surgical tool, such that each movement of each surgical tool is stored; determining said ALLOWED and RESTRICTED movements according to historical movements of said at least one surgical tool, such that said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said 3D spatial positions, and said RESTRICTED movements are movements in which the location of said at least one surgical tool is substantially different from said n 3D spatial positions.

h. said tool-dependent ALLOWED and RESTRICTED movements rule comprises steps of: providing a communicable database; storing predetermined characteristics of at least one said surgical tool; determining said ALLOWED and RESTRICTED movements according to said predetermined characteristics of said surgical tool; such that ALLOWED movements are movements of said endoscope which track said surgical tool having said predetermined characteristics;

i. providing a maneuvering subsystem communicable with said controller, spatially repositioning said at least one surgical tool during a surgery according to said predetermined set of rules; and alerting the physician of said RESTRICTED movement of said at least one surgical tool.

18. The method of claim **11**, additionally comprising at least one of the following sets of steps:

a. selecting said hazards or obstacles in said surgical environment from a group consisting of tissue, a surgical tool, an organ, an endoscope and any combination thereof;

b. comprising said input of n 3D spatial positions, n is an integer greater than or equal to 2; defining at least one of said spatial positions as an ALLOWED location; defining at least one of said spatial positions as a RESTRICTED location; such that said ALLOWED movements are movements in which said at least one surgical tool is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said at least one surgical tool is substantially different from said n 3D spatial positions;

c. comprising said input of at least one rule according to which ALLOWED and RESTRICTED movements of said at least one surgical tool are determined; such that the spatial position of said at least one surgical tool is controlled by said controller according to said ALLOWED and RESTRICTED movements;

d. said operator input rule comprises steps of: converting an ALLOWED movement to a RESTRICTED movement and converting a RESTRICTED movement to an ALLOWED movement;

e. selecting said anatomical element from a group consisting of tissue, organ, another surgical tool and any combination thereof;

f. said right tool rule comprises steps of: determining said ALLOWED movement of said endoscope according to the movement of the surgical tool positioned to right of said endoscope; further wherein said left tool rule comprises steps of: determining said ALLOWED movement of said endoscope according to the movement of the surgical tool positioned to left of said endoscope;

g. said tagged tool rule comprises steps of: tagging at least one surgical tool within said surgical environment and determining said ALLOWED movements of said endoscope to be movements that constantly track the movement of said tagged surgical tool;

h. said field of view rule comprises steps of: providing a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; generating a field of view from the combination of all of said n 3D spatial positions; maintaining a constant field of view by determining said ALLOWED movement of said endoscope to be within said n 3D spatial positions, such that said ALLOWED movements are movements in which said endoscope is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said endoscope is substantially different from said n 3D spatial positions;

i. said preferred volume zone rule comprises steps of: providing a communicable database comprising n 3D spatial positions; n is an integer greater than or equal to 2; generating said preferred volume zone from said n 3D spatial positions; determining said ALLOWED movement of said endoscope to be within said n 3D spatial positions and said RESTRICTED movement of said endoscope to be outside said n 3D spatial positions, such that said ALLOWED movements are movements in which said endoscope is located substantially in at least one of said n 3D spatial positions, and said RESTRICTED movements are movements in which the location of said endoscope is substantially different from said n 3D spatial positions;

j. said preferred tool rule comprises steps of: providing a communicable database, storing a preferred tool in said database; determining said ALLOWED movement of said endoscope so as to constantly track the movement of said preferred tool;

k. said no fly zone rule comprises steps of: providing a communicable database comprising n 3D spatial positions, n is an integer greater than or equal to 2; defining a predetermined volume within said surgical environment from said n 3D spatial positions; determining said RESTRICTED movement to be said movement within said no fly zone; determining said ALLOWED movement to be said movement outside said no fly zone, such that said RESTRICTED movements are movements in which said at least one of said surgical tool is located substantially in at least one of said n 3D spatial positions, and said ALLOWED movements are movements in which the location of said at least one endoscope is substantially different from said n 3D spatial positions;

l. said most used tool rule comprises steps of: providing a communicable database; counting the amount of movement of each said surgical tool; constantly positioning said endoscope to track movement of the most moved surgical tool;

m. selecting said alert from a group consisting of: audio signaling, voice signaling, light signaling, flashing signaling and any combination thereof;

n. defining said ALLOWED movement as a movement permitted by said controller and defining said RESTRICTED movement as a movement denied by said controller;

o. said tool-dependent ALLOWED and RESTRICTED movements rule comprises steps of: providing a communicable database; storing predetermined characteristics of at least one of said surgical tool; determining said tool-dependent ALLOWED and RESTRICTED movements according to said predetermined characteristics of said surgical tool; such that ALLOWED movements are movements of said endoscope which track said surgical tool having said predetermined characteristics;

p. said movement detection rule comprises steps of: providing a communicable database comprising the real-time 3D spatial positions of each said surgical tool; detecting movement of said at least one surgical tool when a change in said 3D spatial positions is received, such that said ALLOWED movements are movements in which said endoscope is re-directed to focus on said moving surgical tool.

19. The method of claim **11**, additionally comprising at least one set of the following steps:

a. comprising said at least one location estimating means of at least one endoscope configured to acquire real-time images of said surgical environment within said human body; providing at least one surgical instrument spatial location software; receiving said real-time images of said surgical environment from said endoscope and estimating said 3D spatial position of said at least one surgical tool using said spatial location software;

b. providing said at least one location estimating means comprising (a) at least one element selected from a group consisting of optical imaging means, radio frequency transmitting and receiving means, at least one mark on said at least one surgical tool and any combination thereof; and, (b) at least one surgical instrument spatial location software configured to estimate said 3D spatial position of said at least one surgical tool by means of said element; and

c. selecting said at least one location estimating means to be an interface subsystem between a surgeon and said at least one surgical tool, the interface subsystem comprising:

   i. at least one array comprising N regular or pattern light sources, where N is a positive integer;

   ii. at least one array comprising M cameras, where M is a positive integer;

   iii. optional optical markers and means for attaching the optical marker to the at least one surgical tool; and;

   iv. a computerized algorithm operable via the controller, the computerized algorithm configured, when executed, to record images received by each camera of each of the M cameras and to calculate therefrom the position of each of the tools, and further configured to provide automatically the results of the calculation to the human operator of the interface; and

d. selecting said predetermined characteristics of said surgical tool from a group consisting of: physical dimensions, structure, weight, sharpness, and any combination thereof.

20. The method of claim **11**, additionally comprising at least one of the following steps:

a. providing said tool with articulations substantially at the tip of said tool, substantially along the body of said tool, and any combination thereof.

b. controlling articulation by means of a method selected from a group consisting of hardware control, software control and any combination thereof.

c. providing a tool articulated at a region selected from a group consisting of near the tip of said tool, on the body of said tool, and any combination thereof.

* * * * *

patsnap

专利名称(译)	用于辅助腹腔镜手术的装置和方法 - 引导和操纵铰接工具		
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[标]申请(专利权)人(译)	M.S.T.医学外科技术有限公司		
申请(专利权)人(译)	M.S.T.医疗手术TECHNOLOGIES LTD.		
当前申请(专利权)人(译)	M.S.T.医疗手术TECHNOLOGIES LTD.		
[标]发明人	ATAROT GAL LEVINSON YARON NIR TAL FRIMER MOTTI		
发明人	ATAROT, GAL LEVINSON, YARON NIR, TAL FRIMER, MOTTI		
IPC分类号	A61B19/00 A61B1/00 A61B1/06 A61B17/00 A61B1/04		
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摘要(译)

一种手术控制系统，包括：手术工具，其可插入人体的手术环境中以进行外科手术。逻辑被配置为在任何给定时间t实时定位至少一个手术工具的3D空间位置。该系统还包括至少一个移动检测器和与控制器数据库通信的控制器。