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(54) **MULTIMODALITY INSTRUMENT FOR TISSUE CHARACTERIZATION**

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**Related U.S. Application Data**

(63) Continuation of application No. 09/017,519, filed on Feb. 2, 1998, now Pat. No. 6,109,270, and a continuation of application No. 08/795,272, filed on Feb. 4, 1997, now abandoned.

(51) **Int. Cl.**<sup>7</sup> ..... **A61B 6/00**

(52) **U.S. Cl.** ..... **600/476; 600/117; 600/300; 606/130; 128/899; 345/156**

(58) **Field of Search** ..... 600/473, 478, 600/476, 466, 464, 435, 434, 342, 407, 117, 114; 606/300, 2; 128/899, 664

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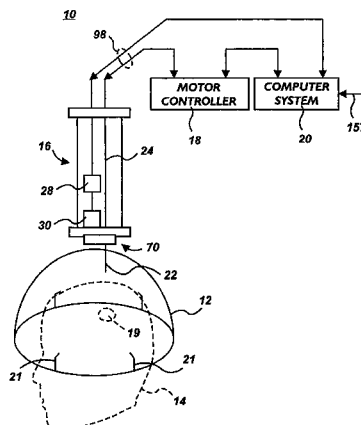
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(57) **ABSTRACT**

A system with multimodality instrument for tissue identification includes a computer-controlled motor driven heuristic probe with a multisensory tip. For neurosurgical applications, the instrument is mounted on a stereotactic frame for the probe to penetrate the brain in a precisely controlled fashion. The resistance of the brain tissue being penetrated is continually monitored by a miniaturized strain gauge attached to the probe tip. Other modality sensors may be mounted near the probe tip to provide real-time tissue characterizations and the ability to detect the proximity of blood vessels, thus eliminating errors normally associated with registration of pre-operative scans, tissue swelling, elastic tissue deformation, human judgement, etc., and rendering surgical procedures safer, more accurate, and efficient. A neural network program adaptively learns the information on resistance and other characteristic features of normal brain tissue during the surgery and provides near real-time modeling. A fuzzy logic interface to the neural network program incorporates expert medical knowledge in the learning process. Identification of abnormal brain tissue is determined by the detection of change and comparison with previously learned models of abnormal brain tissues. The operation of the instrument is controlled through a user friendly graphical interface. Patient data is presented in a 3D stereographics display. Acoustic feedback of selected information may optionally be provided. Upon detection of the close proximity to blood vessels or abnormal brain tissue, the computer-controlled motor immediately stops probe penetration. The use of this system will make surgical procedures safer, more accurate, and more efficient. Other applications of this system include the detection, prognosis and treatment of breast cancer, prostate cancer, spinal diseases, and use in general exploratory surgery.

**22 Claims, 7 Drawing Sheets**



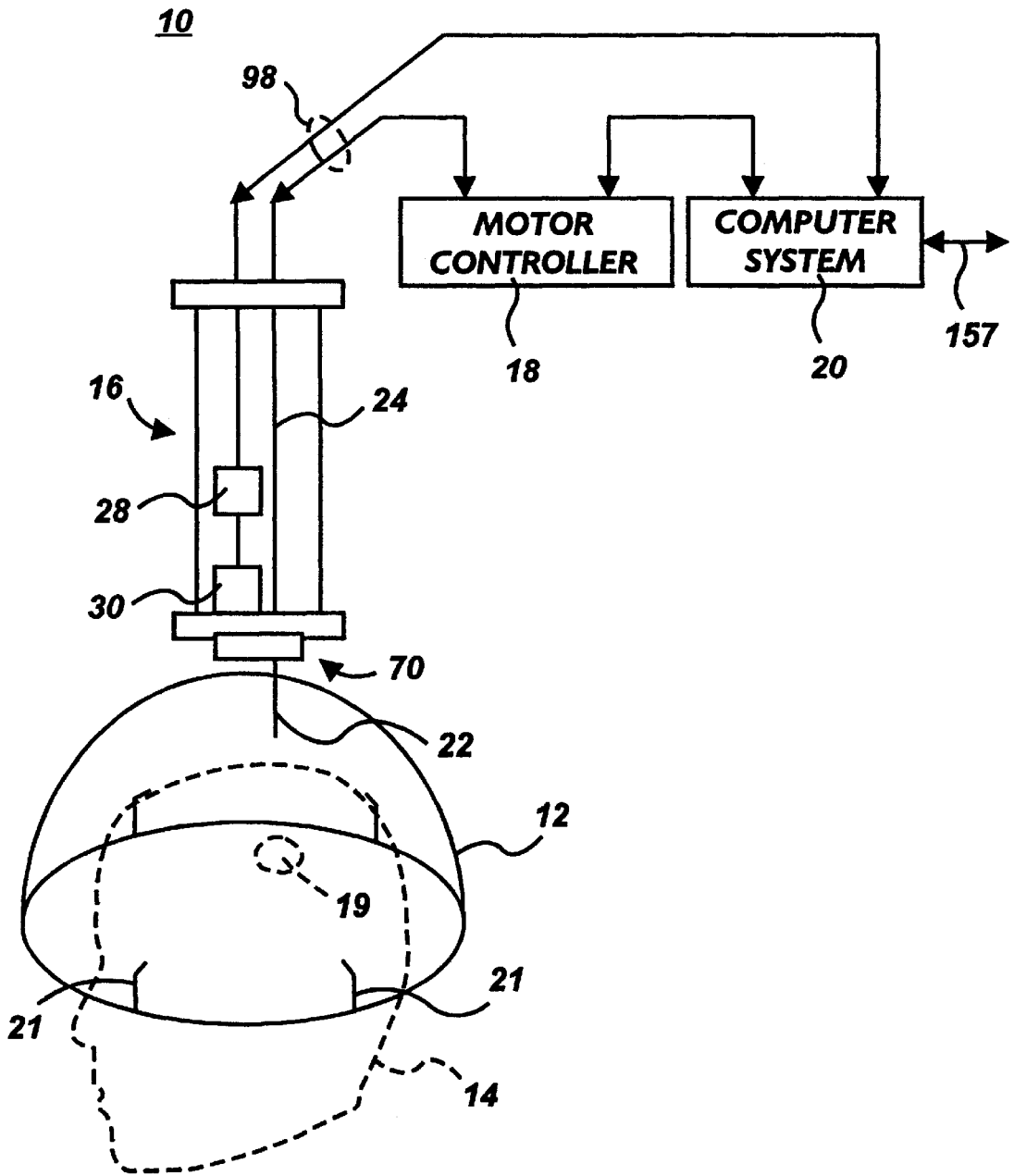


FIG. 1

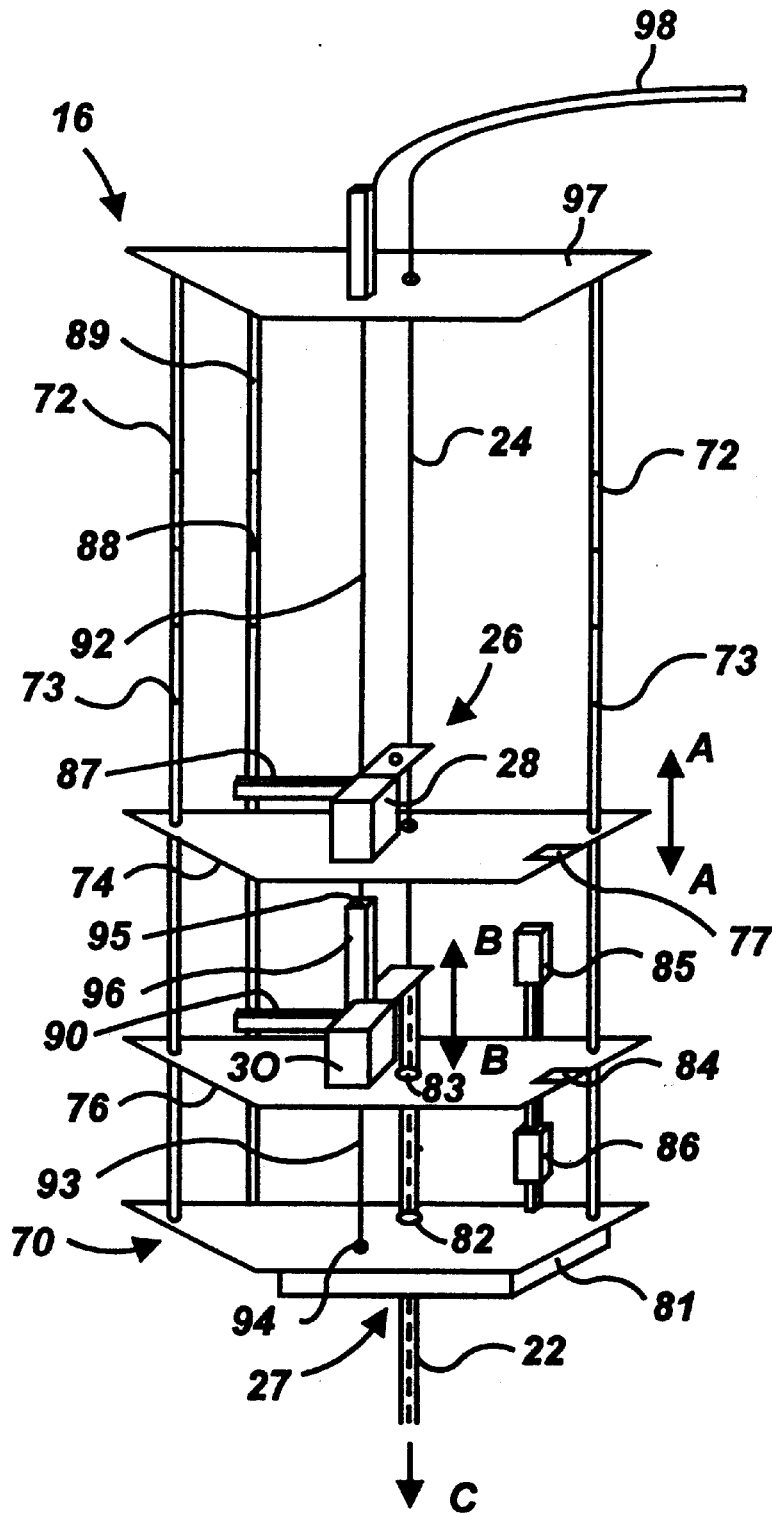


FIG. 2

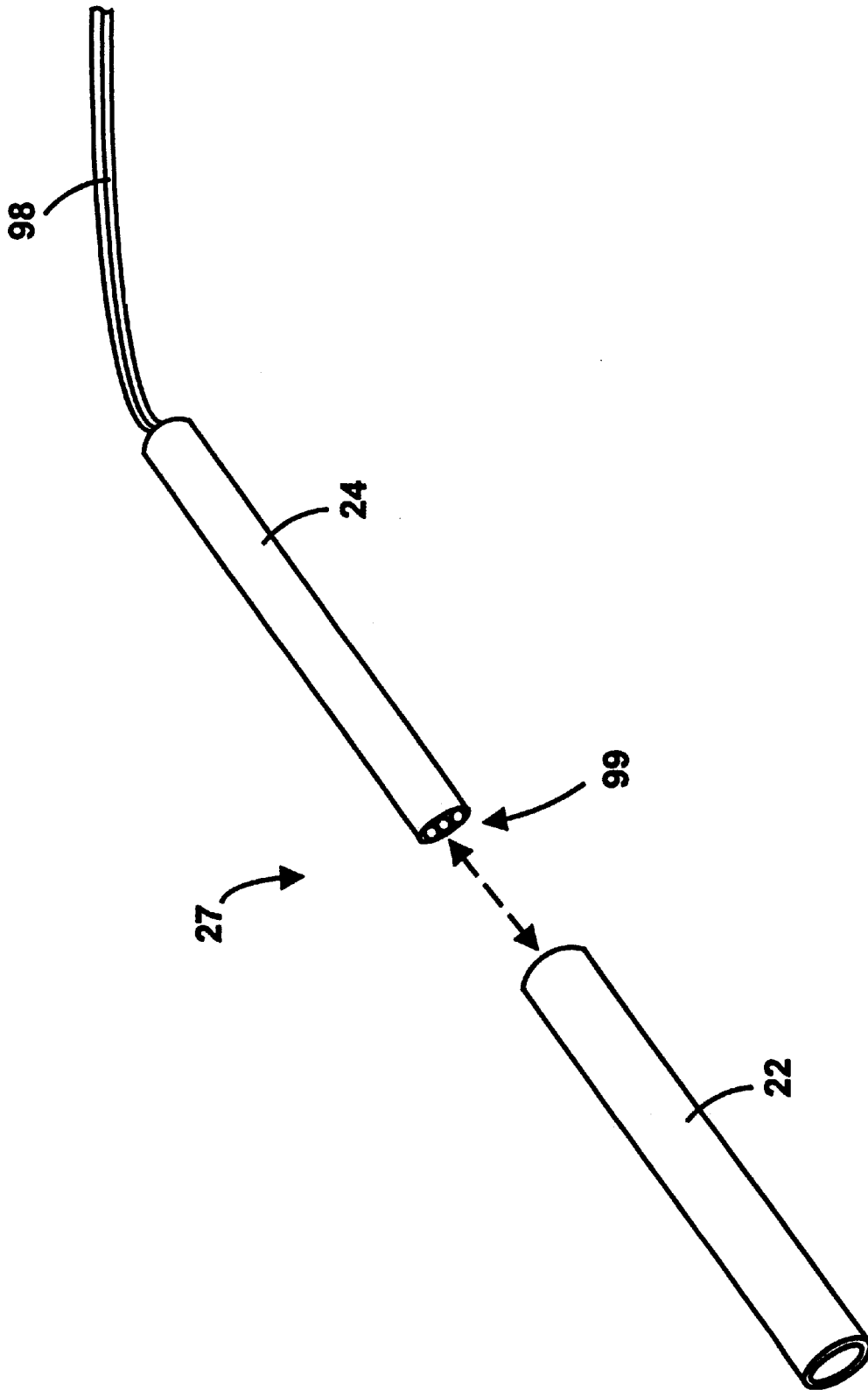
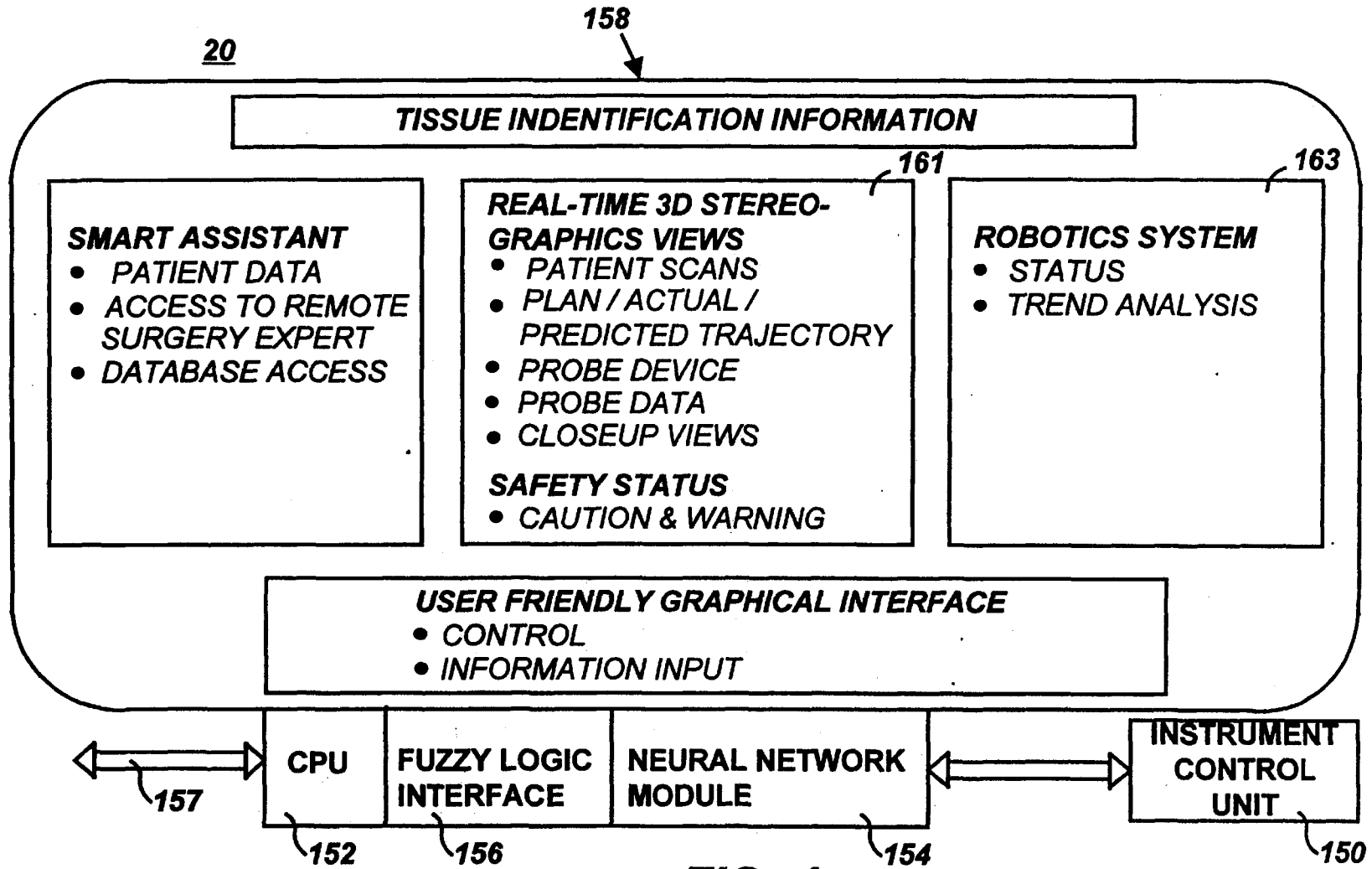
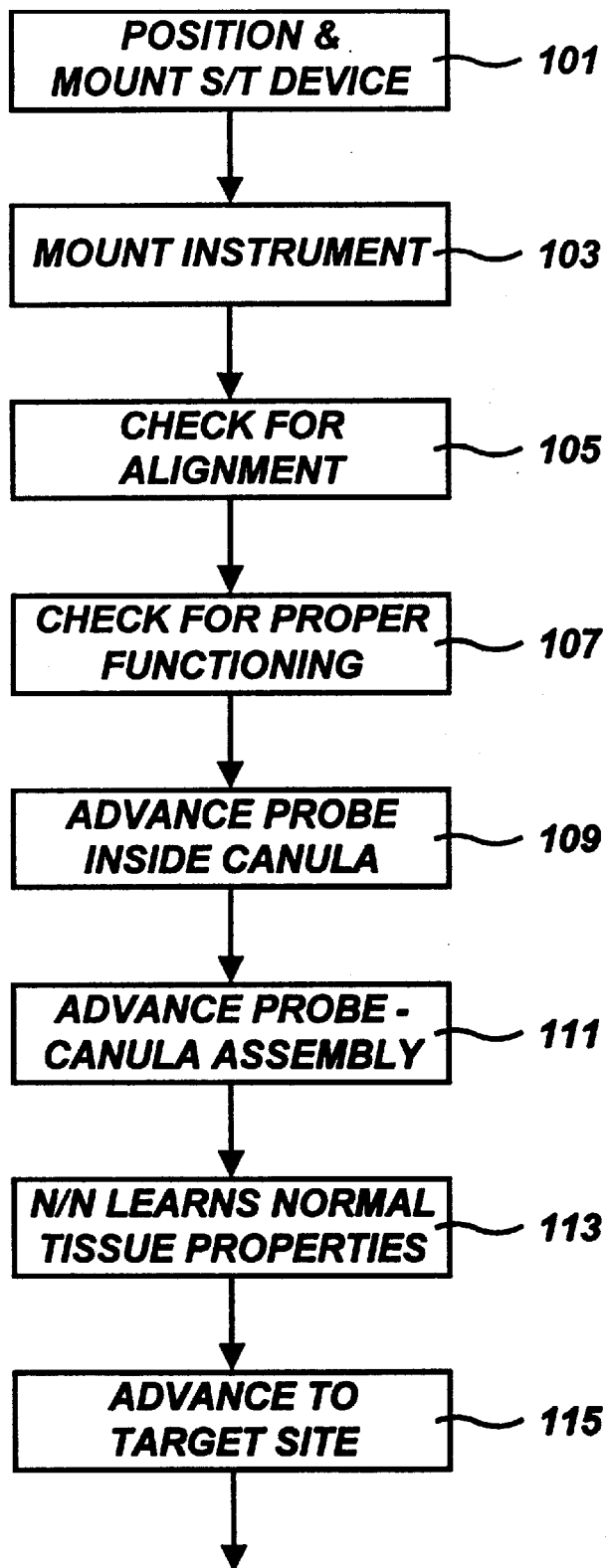


FIG. 3



**FIG. 4**



**FIG.5A**

TO 117

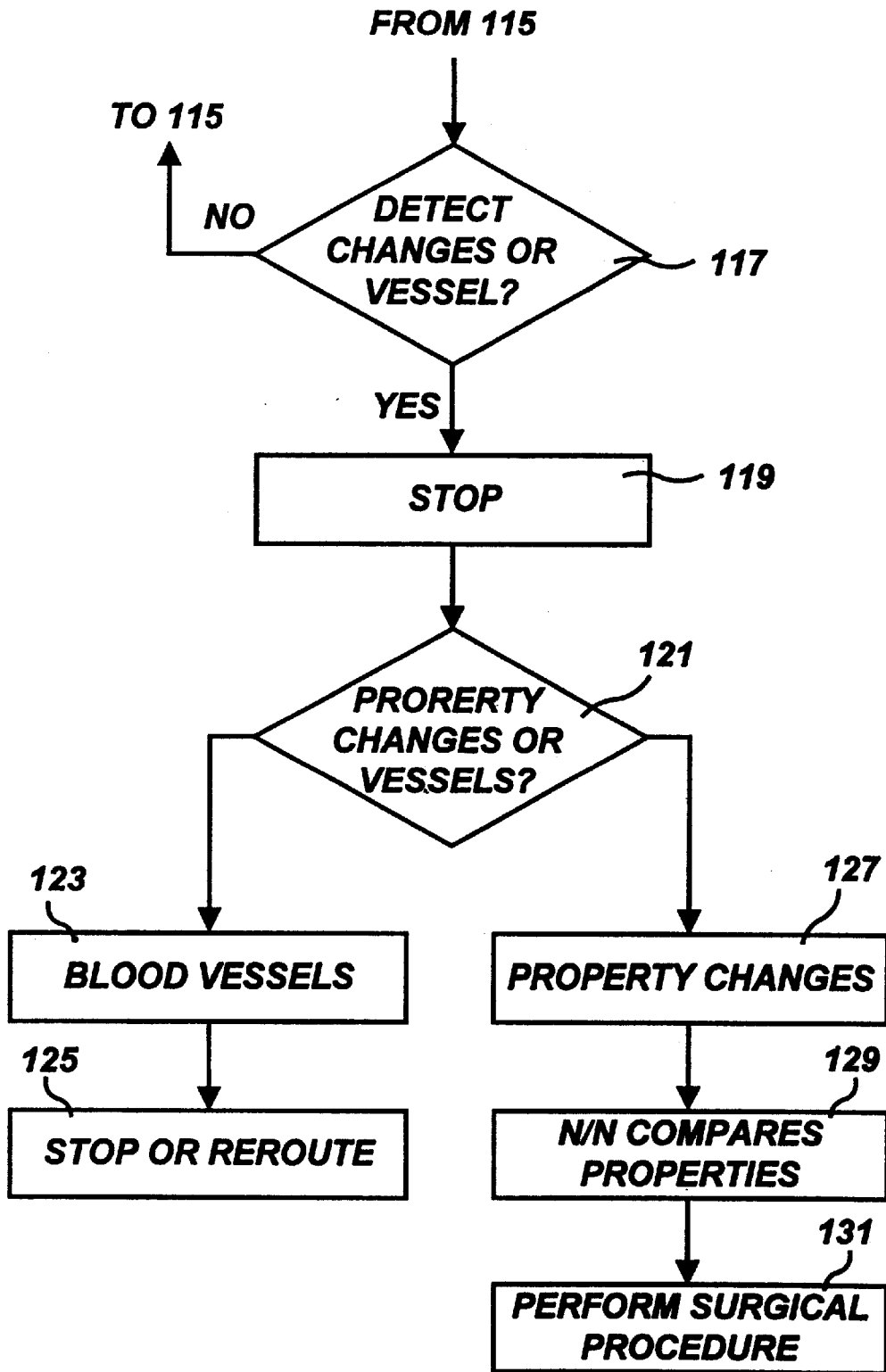


FIG.5B

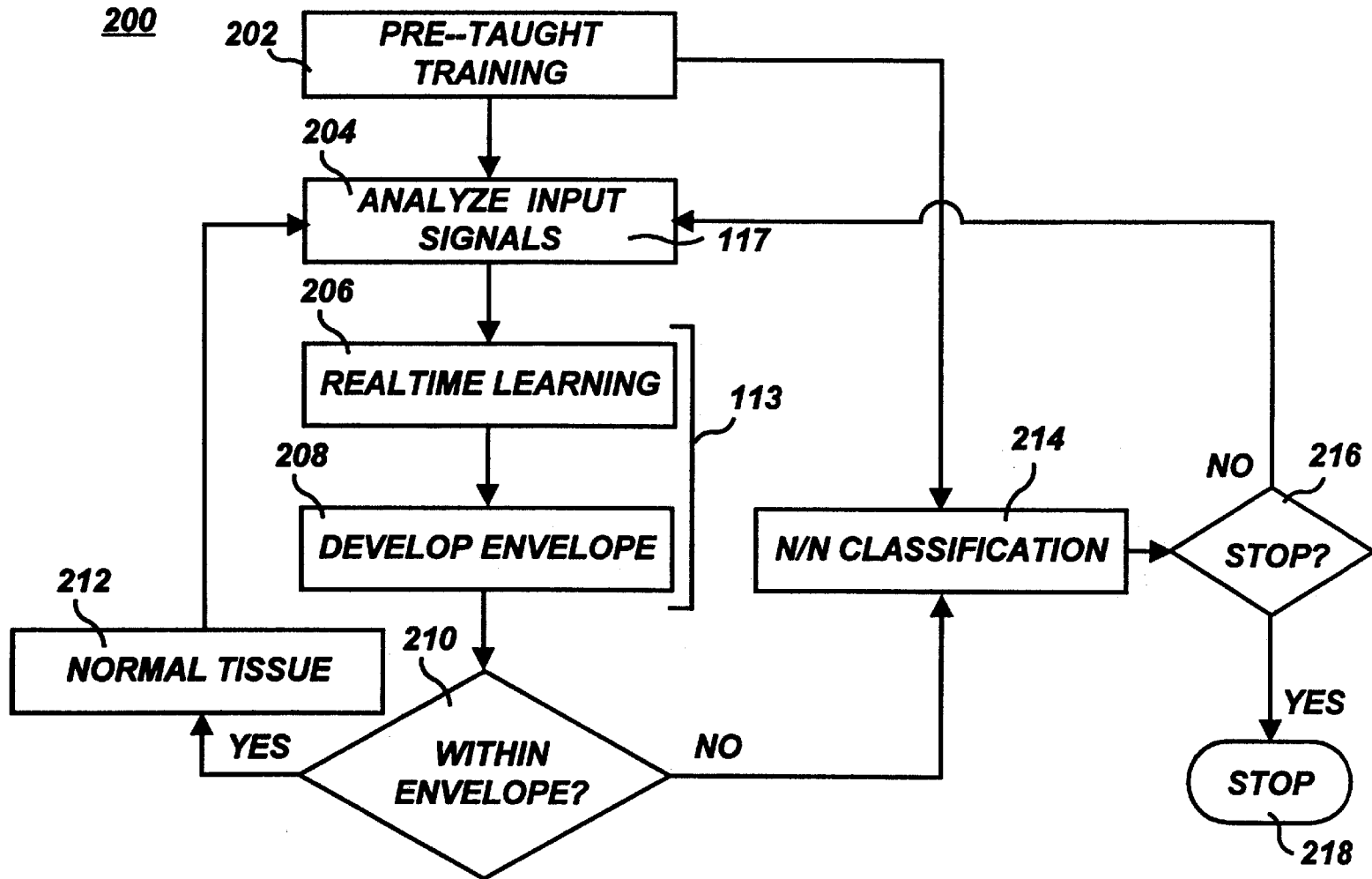


FIG.6



## MULTIMODALITY INSTRUMENT FOR TISSUE CHARACTERIZATION

This application is a continuation of application(s) application Ser. No. 09/017,519 filed on Feb. 2, 1998 now U.S. Pat. No. 6,109,270 application Ser. No. 08/795,272 filed on Feb. 4, 1997 now abandoned.

### ORIGIN OF THE INVENTION

The invention described herein was made by employees of the United States Government and may be manufactured and used by or for the Government for governmental purposes without payment of any royalties thereon or therefor.

### BACKGROUND OF THE INVENTION

#### 1. Technical Field of the Invention

The present invention relates in general to the field of sensors and instruments, and it particularly relates to medical diagnostic, prognostic, treatment and surgical instruments. This invention further relates to a system which heuristically provides tissue identification in neuroendoscopy and minimally invasive brain surgery.

#### 2. Description of the Prior Art

Existing medical instruments provide general diagnoses for the detection of tissue interface such as normal tissue, cancer tumor, etc. However, such detection has been limited clinically to tactile feedback, temperature monitoring, and the use of a miniature ultrasound probe for tissue differentiation during surgical operations. Stereotactic computed tomography (CT) scanners, magnetic resonance imaging (MRI) devices, and similar other instruments provide guided brain biopsy and preoperative scans for use in neurosurgical surgeries. These scans allow samples of brain tissue to be obtained with some degree of accuracy.

However, existing devices provide diagnostic data of limited use, particularly in neurosurgery, where the needle used in the standard stereotactic CT or MRI guided brain biopsy provides no information about the tissue being sampled. The tissue sampled depends entirely upon the accuracy with which the localization provided by the preoperative CT or MRI scan is translated to the intracranial biopsy site. Any movement of the brain or the localization device (e.g., either a frame placed on the patient's head, or fiducials/anatomical landmarks which are in turn related to the preoperative scan) results in an error in biopsy localization. Also, no information about the tissue being traversed by the needle (e.g., a blood vessel) is provided. Hemorrhage due to the biopsy needle severing a blood vessel within the brain is the most devastating complication of stereotactic CT or MRI guided brain biopsy.

Several other drawbacks are associated with existing devices in stereotactic CT or MRI guided brain biopsy. For instance, this procedure is labor intensive and requires the transfer of localization coordinates from the preoperative scan to the localization device. The depth to which the needle is passed within the brain is also subject to human error. No real-time information is gained about either the tissue being biopsied or the tissue being traversed en route to the biopsy site. The biopsy information is not provided on a real-time basis, and may take a day or more for various staining procedures to be performed by the neuropathologist on the sampled tissue. The non-simultaneity of the sampling, analysis and use precludes existing stereotactic CT and MRI guided brain biopsy from being performed remotely, such as in space missions, long term space exploration travels, or hospitals that are not staffed with a neurosurgeon.

CT and MRI scans allow neurosurgeons to identify anatomical regions of the brain with an accuracy on the order of one or two millimeters. As presented later, these scans are not adequate for the precise localization needed by neurosurgeons to perform optimally safe surgery.

CT and MRI scans are obtained pre-operatively. In a conventional stereotactic CT or MRI guided brain biopsy, a frame is applied to the patient's head and the scan obtained. The coordinates of the desired targets on the scan are then translated to corresponding coordinates of the frame. The patient then undergoes the biopsy through a small hole drilled in the skull (three or four millimeters in diameter) using a plastic or metal biopsy "needle" that most commonly aspirates a very small core of tissue (on the order of one or two millimeters in diameter by three or four millimeters in length). Any movement of the brain, such as can be due to changing the position of the patient from the position in which the scan was obtained, can introduce error into the biopsy coordinates.

A much greater practical problem arises when the pre-operative scan is used to guide the removal of a tumor deep within the brain. As the tumor is removed, or the brain retracted to permit access to the tumor, the coordinates from the pre-operative scans become somewhat invalid. This error is especially troublesome with recently developed systems that use an optically-encoded "arm" in an electro-optical camera system for localization during neurosurgical operations.

Another significant problem with using CT and MRI scans for localization is that they do not provide functional localization. As neurosurgical procedures become more precise, the need increases for knowledge of the functional organization of the brain. The localization necessary to perform pallidotomy procedures for Parkinson's disease is one example where anatomical localization based on CT or MRI scanning is inadequate for optimal treatment, since electrophysiological mapping intraoperatively is important to maximize the benefit of the operation for a given patient.

There have been a few recent advances in preoperative scanning that provide some information about the functional organization of the brain. Functional MRI and PET (Positron Emission Tomography) are two examples of such recent scanning techniques. However, these scanning techniques are hampered either by their limited range of functions which can be utilized (e.g., functional MRI) or their relatively poor resolution, for example on the order of one half to one centimeter (e.g., PET).

### SUMMARY OF THE INVENTION

It is an object of the present invention to enable the placement of multiple neurosurgical sensors and/or effectors (or tools), such as a biopsy probe in any desired region of the brain with extreme accuracy.

Another object of the present invention is to enable the localization of the neurosurgical sensors and/or effectors based on the characteristics of the local brain environment, taking into consideration the anatomical and functional variability among human (and non-human) brains.

Still another object of the present invention is to perform minimally invasive surgery, for example the localized placement of the effector and treatment with minimal disruption of normal brain functions. An important method for minimizing invasiveness is miniaturization.

Yet another object of the present invention is the automation of part of surgical procedures. This objective is realized by incorporating two disciplines. The first discipline

is robotics and remote control, and the second discipline is neural net (or artificial intelligence) learning. Remote control has been used by NASA scientists in missions either too dangerous or impossible for human performance, such as sending an unmanned submarine beneath the Antarctic ice cap and a robotic rover into an Alaskan volcano crater. Neural net learning allows a computer to gather information from repeated exposures to normal and abnormal brain tissue which can then be applied to a novel situation, in order to decide the type of tissue being encountered.

A further object of the present invention is to provide a heuristic robotic system with a multimodality instrument for tissue identification. This instrument will replace "dumb" metal needles used to perform exploratory surgeries such as biopsies. It will also help avoid certain complications associated with the translation of the lesion (e.g., tumor) coordinates from MRI/CT scans to the actual lesion using the inventive multimodality instrument. These complications include the inability to obtain tissue which will allow the neuropathologist to make a diagnosis, and the risk of severing a blood vessel which may result in a hemorrhage causing significant neurological injury or possibly death.

Briefly, the foregoing and other features and advantages of the present invention are realized by a robotics system with a multimodality heuristic instrument for tissue identification. The instrument includes a computer-controlled motor driven probe with a multisensory tip, e.g., a group of sensors may be selectively incorporated into the probe tip, or near the probe tip or as part of the probe.

In a preferred embodiment, the probe is driven by a computer-controlled actuator mechanism to the appropriate depth within the brain for obtaining a continuous and real time output of resistance or density of the tissue being penetrated. This output is received into a neural net learning program which is constantly learning not only the differences between normal brain tissue and abnormal brain tissue, such as tumors, but also the differences between various regions of the brain (e.g., gray matter versus white matter).

In another embodiment where robotic insertion is not advantageous, the probe can be a hand-held device and/or manually driven instead of motor driven.

The instrument further includes a micro laser-Doppler blood flow probe having a diameter of less than approximately 1 mm. This probe detects blood vessels before it can disrupt them, and it can further catalog the blood flow differences between either normal brain tissue, abnormal brain tissue, or various regions of the brain such as gray matter and white matter (which are known to have a roughly fivefold difference in blood flow). A micro ultrasound probe, also less than approximately 1 mm in diameter, can aid in blood vessel detection and tissue identification. A  $pO_2$  (partial pressure of oxygen) microprobe, less than 1 mm in diameter can aid in the detection of hypoxia which is an indication of tumor malignancy.

Ion-selective micro electrodes can also be used to monitor such important parameters as pH, calcium, sodium, potassium, and magnesium. Additionally, optical fluorescence and/or optical absorbance probes with a diameter of less than approximately 1 mm can also be used to monitor oxygen and carbon dioxide levels and other parameters of the signal. The combination of optical reflectance sensors and neural net learning to characterize the tissue being penetrated by the probe yields a characteristic optical reflectance signature which is very valuable in distinguishing and identifying different tissues, such as blood vessels, tumors, gray matter and white matter.

The present multimodality instrument offers several advantages and can be used in various commercial applications. For example, the present instrument improves the diagnostic accuracy and precision of general surgery, with near term emphasis on stereotactic brain biopsy. It automates tissue identification with emphasis on stereotactic brain biopsy to permit remote control of the procedure. It also reduces morbidity of stereotactic brain biopsy. The present instrument may also be used in conjunction with various surgical tools to increase the safety, accuracy and efficiency of surgical procedures. For example, the use of the multimodality instrument for monitoring patients with severe head injuries would greatly enhance the surgeon's capabilities in neurosurgery.

The present instrument may also be used in conjunction with endoscopes for tissue identification in various types of surgery, and can be adapted to a hand held device and/or manually driven instead of motor driven for procedures where the automated robotic aspect is not advantageous.

The present instrument may be used in a variety of applications including but not limited to tumor ablation in neurosurgery, general exploratory surgery, prostate cancer surgery, breast cancer surgery, spinal surgery automated tissue identification for general surgery use (e.g., detecting the interface between normal tissue, cancer, tumor, or other lesion), automated stereotactic biopsy for neurosurgery, continuous monitoring for patients at risk for cerebral ischemia and/or increased intracranial pressure (e.g., many patients with cerebrovascular disease, tumors, or severe head injury), and other surgical procedures that could be performed in an automated/robotic fashion for minimizing trauma to the patient because of decreased exposure time in comparison with procedures performed manually and/or more invasively.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The above and other features of the present invention and the manner of attaining them will become apparent, and the invention itself will be best understood, by reference to the following description and the accompanying drawings, wherein:

FIG. 1 is a perspective schematic view of a robotic system configuration incorporating a multimodality instrument (shown schematically) according to the present invention;

FIG. 2 is an enlarged view of the instrument shown in FIG. 1;

FIG. 3 is a greatly enlarged view of a probe-cannula assembly comprised of a multimodality probe and a cannula for use in the instrument of FIGS. 1 and 2;

FIG. 4 is a schematic view of a monitor forming part of the robotic system of FIG. 1, illustrating an exemplary user interface graphics display forming part of a computer system;

FIGS. 5A and 5B represent a flow chart illustrating the general use of the robotic system of FIG. 1; and

FIG. 6 is a flow chart illustrating the learning process of the heuristic system of FIG. 1.

Similar numerals refer to similar elements in the drawing. It should be understood that the sizes of the different components in the drawings are not in exact proportion, and are shown for visual clarity and for the purpose of explanation.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates a robotics heuristic system 10 configured pursuant to the present invention. The system 10

generally includes a stereotactic device **12** mounted on a subject's head **14**; a robotics instrument **16**; motor controller **18**; and a computer system **20**. While the system **10** will be described in connection with a neurosurgical application, it should be clear that the system **10** may be adapted for use in various other medical and non medical applications.

The stereotactic device **12** is mounted on the subject's head **14** and is affixed to the skull by means of retaining screws or pins **21**. The stereotactic device **12** further assists in locating a target site, for example a brain tumor **19**, by providing a fixed reference or fiducial coordinate system. The stereotactic device **12** is well known in the field and is commercially available from Radionics, under the trade name BRW/CRW stereotactic systems. In other applications the stereotactic device **12** may be replaced with another suitable fixation device, such as a "helmet" which conforms precisely to the subject's head **14**, and/or a device, such as an optical system that can be referenced to the preoperative CT or MRI scan.

The robotic instrument **16** is mounted on the stereotactic device **12**, and enables one or more sensors and/or one or more tools to be handled in a precisely controlled fashion. In the present illustration for instance, a cannula **22** (within which a probe **24** is lodged) is designed to automatically penetrate the subject's brain with an extremely high degree of precision. In another embodiment, the probe-cannula assembly **27** also shown in FIG. **3** and formed of the cannula **22** and the probe **24** can be replaced with a probe-tool assembly wherein the tool is capable of performing various mechanical functions and medical treatment.

The robotic instrument **16** includes an actuator mechanism **26** capable of driving the sensors and/or tools with minimal damage to the brain tissue. In the present illustration the actuator mechanism **26** includes two stepper motors **28**, **30** that automatically drive the probe **24** inside the cannula **22**, and that further drive the probe-cannula assembly **27** into the brain tissue.

The actuator mechanism **26** is controlled by the motor controller **18** and the computer system **20**. The computer system **20** further includes a neural network program (comprised of a combination of neural networks) used to adaptively learn the information derived by the instrument **16**, for instance resistance and image features of normal brain tissue during the surgery. Fast learning neural networks are used to provide near real-time modeling, and a fuzzy logic interface to the neural network program is used to incorporate expert medical knowledge in the learning process. Identification of abnormal brain tissue is determined by the detection of change and comparison with previously learned models of abnormal brain tissues. Where the automated robotic aspect is not advantageous the drive mechanism may be replaced with a manually-driven mechanism or inserted directly by hand.

The components of the robotics heuristic system **10** will now be described in greater detail in connection with FIGS. **2**, **3** and **4**. Starting with the instrument **16**, it is comprised of a mounting structure **70**; two guide rails **72**; a probe mounting plate **74**; a cannula mounting plate **76**; the actuator mechanism **26**; the cannula **22**; and the probe **24**.

The mounting structure **70** generally includes a base **81** that removably and adjustably mates with the stereotactic device **12** and provides a mounting interface for the actuator mechanism **26**. The base **81** may be made of any suitable light weight material, such as aluminum, and may assume various shapes that best suit the application for which it is used. The base **81** includes an opening **82** that serves as a guide for the cannula **22**.

The two guide rails **72** serve as a guide mechanism, and extend from the base **81** and serve as guides for the probe mounting plate **74**, for it to translate slidably along a desired direction with minimal or no pitch or roll deviation. The rails **72** may include markings **73** for providing a visual indication as to the position of the probe **24** relative to the base **81**. It is conceivable to replace the two rails **72** with an appropriate guide mechanism for the actuator mechanism **26**. In another embodiment the guide mechanism allows the actuator mechanism **26** to rotate around one rail **72** and to further translate linearly in one or more predetermined direction.

The probe mounting plate **74** provides a means for securely holding the motor **28** and the probe **24**. The probe mounting plate **74** includes two adjacent openings through which the probe mounting plate **74** is allowed to journey slidably along the rails **72** for translation along the direction of the arrow A—A. In one exemplary illustration the direction of the arrow A—A coincides substantially with the vertical direction. One or more strain gauges **77** may be secured to the upper surface and/or lower surface of the probe mounting plate **74** to measure pressure or another parameter acting on the cannula **22** or the probe **24**.

As a safety feature, an adjustable mechanical stop **85** is mounted on the base **81** to limit the amount of travel of the probe **24** in and through the cannula **22**. For example, it is possible to initially limit the probe insertion into the cannula **22** up but not exceeding the tip of the cannula **22**. Subsequently, the mechanical stop **85** can be adjusted to allow the probe to extend beyond the cannula tip to another limit for the purpose of deploying a probe effector.

The cannula mounting plate **76** provides a means for securely holding the cannula **22**. The cannula mounting plate **76** includes an opening **83** through which the cannula **22** is inserted for translation in the direction of the arrow B—B. In this exemplary illustration the direction of the arrow B—B coincides with that of the arrow A—A, though it is conceivable to design the system **10** such that the probe **24** and the cannula **22** translate along two different directions, at least before they mate.

The cannula mounting plate **76** serves as a retention guide to the cannula **22** and is adjustably moveable relative to the base **81** along the direction of the arrow B—B. One or more strain gauges **84** may be secured to the upper surface and/or lower surface of the cannula mounting plate **76** to measure pressure or another parameter.

The cannula mounting plate **76** also serves as a safety mechanism for limiting the travel of the probe-cannula assembly **27** beyond a predetermined level inside the brain. To this end, as the cannula mounting plate **76** reaches the base **81**, or a predetermined distance above the base **81**, it stops the advancement of the cannula **22** inside the brain tissue. The distance between the cannula mounting plate **76** and the base **81** may be adjusted even when the cannula mounting plate **76** has reached a predetermined position, by means of an adjustable mechanical stop **86** provided for limiting the travel of the cannula mounting plate **76**.

A position encoder **87** may be mounted on the probe mounting plate **74** to provide information on the position of the probe **24** relative to a reference mark on the base **81**, or relative to markings **88** on a graded ruler **89**. Similarly, a position encoder **90** may be mounted on the cannula mounting plate **76** to provide information on the position of the cannula **22** relative to the reference mark on the base **81**, or relative to markings **88** on the ruler **89**.

The actuator mechanism **26** includes the two motors **28**, **30** and their corresponding lead screws **92** and **93**, respec-

tively. The motor **30** is a stepper motor as is generally known in the field. In this particular illustration the motor **30** is available from Air Pax Corporation, in California, as model number L 9 2211-P2. The motor **28** is generally similar to the motor **30**. It should however be clear that another suitable drive mechanism may alternatively be used to drive the cannula **22** by itself or in combination with the probe **24**.

The motor **30** is fixedly secured to the cannula mounting plate **76** via the motor housing, and is further secured to the base **81** by means of the lead screw **93**. To this effect, one end **94** of the lead screw **93** is affixed to the base **81**, and the opposite end of the lead screw **93** is free. The housing of the motor **30** traverses the lead screw **93**. As the motor **30** runs, it causes its housing to translate linearly in the direction of the arrow B—B, thus driving the cannula mounting plate **76** and the cannula attached thereto.

The lead screw **92** extends through the housing of the motor **28** and the probe mounting plate **74**, and operates similarly to the lead screw **93**. One end **95** of the lead screw **92** is affixed to the cannula mounting plate **76**, the housing of the motor **30**, or to a guide **96** extending from, and secured to the probe mounting plate **74**. The opposite end of the lead screw **92** is affixed to a top base plate **97**. As the motor **28** runs, the housing of motor **28** traverses the lead screw **92** to move linearly in the direction of the arrow A—A, thus driving the probe mounting plate **74** and the probe **24** attached thereto toward the cannula **22**.

The cannula **22** is a hollow tubular member that is known in the field. The cannula **22** and the probe **4** are available from Chorus, located in Minnesota, as models 2120 and Archo PEN. The cannula **22** may include markings that provide the surgeon with a visual indication as to the insertion progress of the probe-cannula assembly **27** within the brain tissue. In another embodiment the cannula **22** may be replaced with a suitable guide mechanism or eliminated all together.

The probe **24** is a multimodality probe and is tightly secured to the probe mounting plate **74**. The probe **24** is connected to a power, signal and data cabling **98** that electrically and/or optically connects the instrument **16** to the motor controller **18** and the computer system **20**. The cabling **98** is supported mechanically by any suitable support means (not shown) to prevent the cabling **90** from excessive bending.

As illustrated in FIG. 3, the probe **24** may include one or more of the following sensors and effectors (or tools) **99**, although the following or other types of sensors and/or tools may alternatively be used depending on the application for which they are used:

Strain gauge for measuring the penetration resistance. For example, the strain gauge is available from Entran Devices Corporation, located in New Jersey, as model number EPIH-111-100P/RTV.

Wick in needle microprobe for measuring interstitial pressure.

Laser Doppler blood flow sensor for measuring the proximity of the blood vessels to the cannula tip as well as the rate of blood flow. For example, the laser Doppler blood flow sensor is available from VASAMEDICS, located in Minnesota, as model number BPM<sup>2</sup>.

Ultrasound probe for tissue identification.

Endoscope for providing image data. For example, the endoscope is available from Johnson & Johnson Professional, Inc., as model number 83-1337.

pO<sub>2</sub> (partial pressure of oxygen) microprobe for measuring hypoxia.

Laser and/or other optical sensors for measuring the reflectance properties of tissues.

Temperature sensor to measure tissue temperature.

Ion specific sensors to measure the concentration of specific ions.

Microelectrode to measure brain electrical activity.

Tissue ablation laser.

Effectors such as: biopsy forceps, malleable biopsy forceps, grasping forceps, micro-scissors, coagulator, irrigator.

The general use and operation of the system **10** will now be described in connection with FIGS. 5A and 5B. The surgeon starts by positioning the stereotactic device **12** on the subject's head **14**. The stereotactic device **12** which is then mounted and tightly secured in place (block **101**). A CT or MRI scan can be obtained with the stereotactic device **12** in place is used to relate the procedure to a prior CT or MRI scan. A hole may be drilled in the subject's skull at a predetermined site, either manually or robotically using the system **10**.

Having selected the proper sensors and/or tools forming part of the probe **24**, the surgeon mounts the Instrument **16** on the stereotactic device **12** (block **103**) and calibrates the instrument **16**, by checking the alignment of the probe **24** relative to the cannula **22** (block **105**) and then checking the proper functioning of the instrument **16**, the motor controller **18** and the computer system **20** (block **107**).

With the motor **30** in a non-operative mode and the cannula mounting plate **76** stationed at a predetermined marking **88**, the surgeon advances the probe **24** toward the cannula **22** (block **109**) by means of the motor **28**, until the probe **24** is housed in its proper position within the cannula **22**. At which time the motor **28** is locked in position. In some embodiments of the system **10** it is desirable to have the tips of the probe **24** and the cannula **22** flush with each other, while in other embodiments, such as when tools are used, the tips of the probe **24** and the cannula **22** are not flush. As an example, the tip of the probe **24** may extend beyond the tip of the cannula **22**.

Once the calibration stage is completed the surgeon starts the surgical stage by instructing the computer system **20** to advance the probe-cannula assembly **27** into the brain normal tissue (block **111**) at a predetermined controlled speed. The advancement of the probe-cannula assembly **27** is performed by operating the motor **30**, which causes the probe mounting plate **74**, the motor **28**, the cannula mounting plate **76**, and the probe-cannula assembly **27** to be driven simultaneously forward in the direction of the arrow C.

As the probe-cannula assembly **27** is advancing into normal tissue the neural network program within the computer system **20** learns the properties of the normal tissue (block **113**) for further processing, as will be described later. In certain applications it might be desirable to stop the advancement of the probe-cannula assembly temporarily until sufficient data is collected or to provide the neural networks of the computer system **20** sufficient time to learn.

When either the surgeon or the computer system **20** determines that sufficient data have been collected, the actuator mechanism **26** is instructed to advance the probe-cannula assembly to a predetermined target site (**115**), for example tumor **19**. The computer system **20** continually checks to determine whether changes in the tissue properties or blood vessels have been detected (block **117**). If the computer system **20** does not detect property changes or blood vessels, it instructs the probe-cannula assembly **27** to continue its travel toward the target site (block **115**). If on the

other hand the computer system **20** detects property changes or blood vessels then it instructs the probe-cannula assembly **27** to stop advancing (block **119**).

Based on the detection result (block **117**) the computer system **20** notifies the surgeon of the appropriate action to be taken. As an example, the computer system **20** determines whether it has detected tissue property changes or blood vessels (block **121**). If the computer system **20** detects the proximity of blood vessels then the surgeon takes the appropriate corrective measures, such as to stop the surgery or to reroute the probe-cannula assembly **27** (block **125**). These corrective measures will enable the surgeon to avoid injury to the blood vessels.

If however, the computer system **20** detects tissue property changes (block **127**), the neural networks compare the measured tissue properties and/or measured changes in tissue properties to previously learned properties and to reference properties (block **129**). At this stage the surgeon will confidently perform the necessary surgical procedure (block **131**).

A few exemplary surgical procedures that can be performed using the system **10** are:

Automated tissue identification for general surgery use, for detecting the interface between normal tissue, cancer, or tumor. For example, surgery to remove prostate cancer can be accomplished accurately with minimal damage to normal tissue.

Automated stereotactic biopsy for neurosurgery.

Continuous monitoring for patients at risk for cerebral ischemia and/or increased intracranial pressure.

With the development of multimodality effectors as well as multimodality sensors on the neurosurgical probe, many neurosurgical procedures could be performed in an automated/robotic fashion, thus minimizing trauma to the brain tissue because of the decreased exposure needed in comparison to open procedures performed by a neurosurgeon manually. Examples include the precise placement of (a) electrodes (epilepsy), (b) chemotherapeutic agents or radiation seeds (brain tumors), and (c) transplanted tissue (movement disorders such as Parkinson's disease). Increased precision of intraoperative localization and excision (or ablation with a laser beam) of deep brain lesions would be possible.

In vivo injection of chemicals and tissue.

Scientific and animal research.

In one embodiment of the system **10**, once the target site has been detected and reached, the sensing probe **24** is retracted from the cannula **22** by reversing the operation of the motor **28**. A substitute probe, for instance a probe **24** containing tools, can then be positioned inside the cannula **22** as described above, for aiding in the surgical procedure.

For neurosurgical biopsy applications, the instrument **16** is mounted on the stereotactic frame **12** in order to have the biopsy probe **24** penetrate the brain in a precisely controlled fashion. The resistance of the brain tissue being penetrated is monitored by a miniature (e.g., 0.050 inch-diameter) circular strain gauge **93** attached to the tip of the biopsy probe **24**. Other modality sensors such as a miniature endoscope or laser Doppler blood flow sensor are mounted near the probe tip to provide real-time tissue images and the ability to detect the proximity of blood vessels.

The motor controller **18** drives, and precisely controls the motors **28**, **30**. In a preferred embodiment the motor controller **18** includes a circuit board that includes control logic for generating commands. The motor controller **18** is available from Motion Engineering, Inc., located in California, as

model number PCX/DSP-800. The motor controller **18** further includes an amplifier that generates the electrical current to drive the motors. The amplifier is available from Haydon Switch & Instrument, Inc., located in Connecticut, as part number 39105. Some or all of the motor controller **18** may be installed internally or externally relative to the computer system **20**.

With reference to FIG. 4, the computer system **20** generally includes an instrument control unit **150**, a central processing unit (CPU) **152**, a neural network module **154**, a fuzzy logic interface **156**, and a three-dimensional (3D) graphics interface **158**.

The instrument control unit **150** controls the various sensors and tools and performs signal processing for the various sensors and tools of the probe **24**. As an example, the instrument control unit **150** can change the brightness and contrast of images generated by an endoscope; change the sensitivity of a laser Doppler; switch laser sources; interpret reflectance signals; turns tools ON and OFF, etc.

The CPU **152** may have any suitable speed, for example 200 MHZ, for acquiring data, signal processing; controlling the graphics display; and providing a user friendly interface. The computer system **20** may be connected via a suitable communication link **157** to remote computers or other systems, which, for example enable the remote operation and control of the system **10**.

The neural network module **154** is used to adaptively learn the information provided by the instrument **16**. As an example, the neural network module **154** can learn the characteristics of a particular subject's normal brain tissue, such as resistance, color, size, shape, patterns, reflectance and other factors associated with the various types of sensors and tools listed herein, while the surgery is being performed. Fast learning neural networks are used to provide near real-time modeling. The fuzzy logic interface **156** is added to the neural networks to incorporate expert medical knowledge in the learning process.

Neural networks have described in several publications, for instance "How Neural Networks Learn from Experience", by G. H. Hinton, Scientific American, September 1992, pages 145-151. However, the combination of various neural networks and the fuzzy logic interface **156** to automatically conduct important aspects of complicated surgical processes telemetrically, interactively with the surgeon, and with minimal risks to the patients is believed to be new.

The neural network module **154** will now be described in greater detail in connection with FIG. 6 which illustrates the learning process **200** of the heuristic system **10**. The neural network module **154** is trained (block **202**), in combination with the fuzzy logic, to create a model of various types of tissues. The training is carried out using one or a combination of suitable hybrid neural networks, including but not limited to:

Backpropagation.

Radial basis function (RBF).

Infold self organizing feature map.

Cerebellar model articulation computer (CMAC).

For near real-time modeling of brain tissue, radial basis function (RBF), Infold self organizing feature maps and cerebellum model arithmetic computer (CMAC) neural networks are used in various combinations to provide fast learning and enhanced modeling. Data used for learning include (1) instrument sensor data that has been signal processed to provide a set of parameters which captures the main characteristics of the tissue; (2) expert knowledge data that has been processed through fuzzy logic to provide a set

of parameters to aid in the modeling of the tissue being penetrated; and (3) tissue identification data provided by pre-trained neural networks to aid in the classification of the tissue being penetrated.

Pre-trained neural networks are neural networks which have been trained using reference tissues and which are continually being updated based on instrument sensor data obtained from surgery and confirmed tissue type from laboratory test results of the biopsied tissue.

As the probe-cannula assembly 27 advances through normal tissue (block 111), the neural network module 154 analyzes the input signals (block 204) from the instrument 16, and learns, on a near real-time basis (block 206), the specific properties of the normal tissue for the particular subject. The neural network module 154 then develops an envelope or model for the specific properties learned (block 208). The neural network module 154 has the ability to develop a separate envelope for each of the parameters or factors being sensed.

The neural network module 154 then places the envelope on top of the learned model to define the normal range of the specific properties of the normal tissue, and to further identify the range of the properties of abnormal tissue. The neural network module 154 then compares the input signals acquired by the instrument 16 to the envelope and determines whether the input signals fall within the envelope (block 210). If the input signals fall within the normal tissue range defined by the envelope, the neural network module identifies the tissue penetrated as normal tissue (block 212), and the computer system 20 instructs the instrument to keep advancing the probe-cannula assembly 27 toward the target site (block 115).

As the probe-cannula assembly 27 advances through the tissue the neural network module 154 continues learning on a near real-time basis and updating the envelope. The foregoing routine (blocks 204, 206, 208, 210) is repeated for each of the envelopes (if more than one envelope have been developed) until the neural network module 154 determines that the input signals fall outside one or a combination of envelopes of normal properties.

Once such determination is made the neural network module 154 compares the input signals to the pre-taught training model and classifies the tissue type (block 214). For example, identification of abnormal brain tissue is determined by detection of change and comparison with previously learned models of abnormal brain tissues. The computer system 20 then inquires whether or not to stop the advancement of the probe-cannula assembly 27 (block 216). If the surgeon determines that further advancement is required then the routine of data collection, analysis and classification (blocks 204, 206, 208, 210, 214) is continued until such time as the surgeon instructs the computer system 20 to stop the advancement of the probe-cannula assembly 27 (block 218). In certain applications it might be desirable to have the probe-cannula assembly 27 penetrate the abnormal tissue (or tumor) completely and extend beyond it.

The operation of the multimodality system 10 is controlled through the user friendly three-dimensional (3D) graphics interface 158. Real-time tissue identification information is also displayed graphically. Patient data is presented in a three dimensional stereographics display 161. Acoustic feedback of selected information is provided as an aid to the surgeon. Upon detection of the close proximity to blood vessels or abnormal brain tissue, the actuator mechanism 26 immediately stops the probe penetration. The 3D stereographics display 161 is comprised of three orthogonal views of the anatomy, with each view presenting the appro-

prate sequence stack of MRI or CT scans. In each view, a graphical model of the probe is driven in motion in real-time by data incoming from the probe. In addition, the multisensory outputs from the actual probe are displayed graphically in real-time at the probe tip in each view. A closeup of the probe tip is provided to show fine details of the MRI or CT scans as the probe approaches each layer. These views provide a virtual reality environment for visualizing the approach to the target site and the probe proximity to critical arteries.

The 3D graphics interface 158 further includes an indicator 163 for the robotics system that provides an indication as to the status and trend analysis of the system 10. The 3D graphics interface 158 may also provide access to patient records or data, to remote surgery experts and to various databases.

In another embodiment for diagnosis or surgery where robotic insertion is not advantageous, the probe as described above can be a hand-held device inserted by hand into the subject.

While specific embodiments of the present system were illustrated and described in accordance with the present invention, modifications and changes of the system dimensions, use and operation will become apparent to those skilled in the art, without departing from the scope of the invention.

What is claimed is:

1. A method for characterizing tissue, the method comprising:
  - penetrating a patient's body, adjacent to a selected tissue, with a probe, contained in a needle and having at least first and second sensors incorporated therein that are configured to characterize the tissue, where the at least first sensor is drawn from the group of sensors consisting of:
    - a sensor of elastic resistance of a selected portion of the tissue to mechanical deformation of the selected tissue portion;
    - a wick in needle sensor of interstitial pressure associated with the tissue;
    - a laser Doppler sensor of blood flow associated with the tissue;
    - an ultrasonic probe;
    - an endoscope;
    - a sensor of partial-pressure of oxygen associated with the tissue
    - an optical sensor for measuring at least one selected optical property of the tissue;
    - a sensor of a temperature associated with the tissue;
    - an ion-specific sensor of at least one ion associated with the tissue;
    - a microelectrode sensor for measuring at least one selected electrical property associated with the tissue;
    - a mechanical effector; and
    - a tissue ablation laser;
  - and the second sensor is drawn from the group of sensors consisting of:
    - a sensor of partial pressure of CO<sub>2</sub> associated with the tissue;
    - a sensor of a material density associated with the tissue;
    - a fluorescence sensor for measuring fluorescence associated with the tissue;
    - an absorbance sensor for measuring optical absorbance associated with the tissue;
    - a chemical sensor of at least one chemical associated with the tissue;

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a position sensor for estimating present location of the needle within the patient's body; and  
 a velocity sensor for estimating a velocity of the needle relative to a selected location associated with the patient's body;  
 5 acquiring sensor signals from the at least first and second sensors at a sequence of times as the needle penetrates the patient's body; and  
 analyzing the sensor signals acquired by the at least first and second sensors using a computer system including a neural network processing system that receives and adaptively analyzes information from said first and second sensors.  
 10  
 2. The method of claim 1, further comprising comparing information associated with at least one signal received from at least one of said first and second sensors with corresponding information that would be received if said tissue were in a normal medical state.  
 15  
 3. The method of claim 1, further comprising comparing information associated with at least one signal received from at least one of said first and second sensors with corresponding information that would be received if said tissue were in at least one of a tumorous medical state and a cancerous medical state.  
 20  
 4. The method of claim 1, further comprising using said ultrasonic sensor to detect at least one of presence and absence of blood vessels within said tissue and presence and absence of blood vessels adjacent to said tissue.  
 25  
 5. The method of claim 1, further comprising using said ion-specific sensor to measure concentration of at least one of hydrogen ions, hydroxyl ions, calcium ions, sodium ions, potassium ions and magnesium ions present in said tissue.  
 30  
 6. The method of claim 1, further comprising selecting said tissue to be a selected portion of said patient's brain.  
 7. The method of claim 6, further comprising using said probe to detect presence of at least one of cerebral ischemia and intercranial pressure in the selected portion of the brain.  
 35  
 8. The method of claim 1, further comprising providing said probe with a capability to detect presence of an interface between a first tissue that is normal and a second tissue that includes a tumorous or cancerous growth.  
 40  
 9. The method of claim 1, further comprising using said position sensor for estimating a penetration depth of said needle into said patient's body.  
 10. The method of claim 1, further comprising using at least one of said at least first and second sensors to measure blood flow in said tissue and to compare the measured blood flow with at least one reference blood flow value that would be measured if said tissue were in a normal medical state.  
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 11. The method of claim 1, further comprising using at least one of said at least first and second sensors to measure blood flow in said tissue and to compare the measured blood flow with at least one reference blood flow value that would be measured if said tissue were in at least one of a tumorous medical state and a cancerous medical state.  
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 12. A medical device for identifying a medical condition, the device comprising:  
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 a needle capable of penetrating a patient's body, containing a multimodality probe and positioned adjacent to a selected tissue, the probe including at least first and second sensors incorporated therein that are configured to characterize the tissue, where the at least first sensor is drawn from the group of sensors consisting of:  
 a sensor of elastic resistance of a selected portion of the tissue to mechanical deformation of the selected tissue portion;  
 60  
 a wick in needle sensor of interstitial pressure associated with the tissue;

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a laser Doppler sensor of blood flow associated with the tissue;  
 an ultrasonic probe;  
 an endoscope;  
 5 a sensor of partial pressure of oxygen associated with the tissue;  
 an optical sensor for measuring at least one selected optical property of the tissue;  
 a sensor of a temperature associated with the tissue;  
 an ion-specific sensor of at least one ion associated with the tissue;  
 a microelectrode sensor for measuring at least one selected electrical property associated with the tissue;  
 10 a mechanical effector; and  
 a tissue ablation laser;  
 and the at least second sensor is drawn from the group of sensors consisting of:  
 a sensor of partial pressure of CO<sub>2</sub> associated with the tissue;  
 a sensor of a material density associated with the tissue;  
 a fluorescence sensor for measuring fluorescence associated with the tissue;  
 15 an absorbance sensor for measuring optical absorbance associated with the tissue;  
 a chemical sensor of at least one chemical associated with the tissue;  
 a position sensor for estimating present location of the needle within the patient's body; and  
 a velocity sensor for estimating a velocity of the needle relative to a selected location associated with the patient's body;  
 20  
 a computer system, including a neural network processing system, programmed to acquire and adaptively analyze sensor signals from the at least first and second sensors at a sequence of times as the needle penetrates the patient's body and to analyze the sensor signals acquired by the at least first and second sensors to determine if at least one of a first medical condition and a second medical condition is present.  
 25  
 13. The system of claim 12, wherein said computer system is programmed to analyze said sensor signals by comparing information associated with at least one signal received from at least one of said first and second sensors with corresponding information that would be received if said tissue were in a normal medical state.  
 30  
 14. The system of claim 12, wherein said computer system is programmed to analyze said sensor signals by comparing information associated with at least one signal received from at least one of said first and second sensors with corresponding information that would be received if said tissue were in at least one of a tumorous medical state and a cancerous medical state.  
 35  
 15. The system of claim 12, wherein said probe uses said ultrasonic sensor to detect at least one of presence and absence of blood vessels within said tissue and presence and absence of blood vessels adjacent to said tissue.  
 40  
 16. The system of claim 12, wherein said probe uses said ion-specific sensor to measure concentration of at least one of hydrogen ions, hydroxyl ions, calcium ions, sodium ions, potassium ions and magnesium ions present in said tissue.  
 45  
 17. The system of claim 12, wherein said tissue is selected to be a selected portion of said patient's brain.  
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 18. The system of claim 17, wherein said probe uses said probe to detect presence of at least one of cerebral ischemia and intercranial pressure in the selected portion of the brain.

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**19.** The system of claim **12**, wherein said probe has a capability to detect presence of an interface between a first tissue that is normal and a second tissue that includes a tumorous or cancerous growth.

**20.** The system of claim **12**, wherein said probe uses said position sensor to estimate a penetration depth of said needle into said patient's body.

**21.** The system of claim **12**, wherein at least one of said at least first and second sensors has a capability to measure blood flow in said tissue and to compare the measured blood

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flow with at least one reference blood flow value that would be measured if said tissue were in a normal medical state.

**22.** The system of claim **12**, wherein at least one of said at least first and second sensors has a capability to measure blood flow in said tissue and to compare the measured blood flow with at least one reference blood flow value that would be measured if said tissue were in at least one of a tumorous medical state and a cancerous medical state.

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