A Raman probe system includes: a base station; a mobile robot remotely controllable from the base station; a Raman probe assembly supported by the robot, the Raman probe assembly including a laser and a spectrometer; a camera supported by the robot; and a communication subsystem operable to communicate images from the camera and results from the Raman probe assembly to the base station. In some embodiments, a Raman probe system includes: a mobile robot remotely controllable from a base station, the robot including a body and an articulated arm; a camera supported by the robot; a Raman probe assembly supported by the robot, the optical control assembly mounted on the body of the robot; and an optical probe mounted on the articulated arm of the robot; and a wireless communication system operable to communicate images from the camera and results from the Raman probe assembly to the base station.
FIG. 1

FIG. 2

LASER SUBSYSTEM

SPECIMEN

RAMAN SIGNATURE OF SPECIMEN

SPECTROMETER SUBSYSTEM

SPECTROMETER

WAVELENGTH CHARACTERISTICS OF SPECIMEN

ANALYSIS APPARATUS

IDENTIFICATION OF SPECIMEN
FIG. 8
FIG. 14

PROBE BODY

STANDOFF CONE 145

PROTECTED SOURCE & COLLECTION OPTICAL FIBERS

LASER FOCAL POINT (18mm Working Distance)
FIG. 15
METHOD AND APPARATUS FOR CONDUCTING RAMAN SPECTROSCOPY

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This patent application continues a continuation application of and claims priority to U.S. application Ser. No. 11/475,582, filed on Jun. 27, 2006.


[0003] (i) is a continuation-in-part of pending prior U.S. patent application Ser. No. 11/177,940, filed Apr. 29, 2005 by Peidong Wang et al. for METHOD AND APPARATUS FOR CONDUCTING RAMAN SPECTROSCOPY (Attorney's Docket No. AHURA-2230); and

[0004] (ii) claims benefit of pending prior U.S. Provisional Patent Application Ser. No. 60/694,385, filed Jun. 27, 2005 by Kevin J. Knopp et al. for RAMAN IDENTIFICATION SYSTEM (Attorney's Docket No. AHURA-35 PROV);

[0005] both of which are hereby incorporated herein by reference.

TECHNICAL FIELD

[0006] This disclosure relates to methods and apparatus for identifying and characterizing substances in general, and more particularly to methods and apparatus for identifying and characterizing substances using Raman spectroscopy.

BACKGROUND

[0007] Raman spectroscopy is a viable technique for identifying and characterizing a vast array of substances. Raman spectroscopy is widely used in the scientific, commercial and public safety areas.

[0008] Recent technological advances are making it possible to increase the range of applications using Raman spectroscopy through a reduction in cost and size. For example, portable units have recently become available for field use such as the on-site identification of potentially hazardous substances.

[0009] Unfortunately, with Raman spectroscopy, it is generally desirable to bring the optical probe to a position adjacent to the specimen when conducting the Raman spectroscopy. However, this can be a problem in view of the potentially hazardous materials which are to be analyzed, e.g., explosives, chemical agents, toxic industrial chemicals, etc.

[0010] Accordingly, a primary object of the present disclosure is to provide an improved Raman spectroscopy system which overcomes the aforementioned shortcomings of currently available systems.

SUMMARY

[0011] In one preferred embodiment, there is provided an improved Raman probe system in which a remote Raman probe assembly is mounted to a remote control robot for unmanned delivery to a remote specimen. The remote Raman probe assembly includes a wireless communication feature for transmitting information from the remote Raman probe assembly to a base unit. If desired, the wireless communication feature can take the form of a wireless Web link, so as to simplify communication transmission. Furthermore, the remote Raman probe assembly may comprise a Raman probe which may be attached to a robot arm, with the remainder of the remote Raman probe assembly being mounted to the body of the robot, such that the Raman probe can be selectively positioned vis-a-vis the specimen.

[0012] In another form, there is provided a Raman probe assembly for analyzing a specimen, comprising: a light source for generating laser excitation light; a camera for capturing an image; a light analyzer for analyzing a Raman signature; and a light path for (i) delivering the laser excitation light from the light source to the specimen so as to produce the Raman signature for the specimen, (ii) capturing an image of the specimen and directing that image to the camera, and (iii) directing the Raman signature of the specimen to the light analyzer.

[0013] In another form, there is provided a Raman probe assembly for analyzing a specimen, comprising: a light source for generating laser excitation light; a camera for capturing an image; a light analyzer for analyzing a Raman signature; a first light path for delivering the laser excitation light from the light source to the specimen so as to produce the Raman signature for the specimen; a second light path for capturing an image of the specimen and directing that image to the camera; a third light path for directing the Raman signature of the specimen to the light analyzer; wherein the at least a portion of the first light path, the second light path and the third light path are coaxial with one another.

[0014] In another form, there is provided a Raman probe assembly for analyzing a specimen, comprising: a light source for generating laser excitation light; a light analyzer for analyzing a Raman signature; a light path for (i) delivering the laser excitation light from the light source to the specimen so as to produce the Raman signature for the specimen, and (ii) directing the Raman signature of the specimen to the light analyzer; wherein the assembly further comprises a probe body for housing the at least a portion of the light path, and a window, with the light path extending through the window; and further wherein the probe body further comprises a shutter/wiper disposed adjacent to the window.

[0015] In another form, there is provided a Raman probe assembly for analyzing a specimen, comprising: a light source for generating laser excitation light; a light analyzer for analyzing a Raman signature; a light path for (i) delivering the laser excitation light from the light source to the specimen so as to produce the Raman signature for the specimen, and (ii) directing the Raman signature of the specimen to the light analyzer; and wherein the light analyzer comprises a transmitter for transmitting information using an Internet Web protocol.

[0016] In another form, there is provided a method for identifying the nature of a specimen, the method comprising: providing a Raman probe assembly comprising: a light source for generating laser excitation light; a camera for capturing an image; a light analyzer for analyzing a Raman signature; a light path for (i) delivering the laser excitation light from the light source to the specimen so as to produce the Raman signature for the specimen, (ii) capturing an image of the specimen and directing that image to the camera, and (iii) directing the Raman signature of the specimen to the light analyzer wherein the assembly further comprises a probe body for housing the at least a portion of the light path, and a window, with the light path extending through the window; wherein the probe body further comprises a shutter/wiper disposed adjacent to the window; wherein the assembly is carried by a remote controlled robot; providing a base station for receiving the image, and for remotely controlling the robot, and for receiving information from the light analyzer;
navigating the remote control robot from the base station to a position adjacent to the specimen; opening the shutter/wiper; using the camera to aim the probe body at the specimen; energizing the light source so that the laser excitation light is directed at the specimen; and analyzing the return light passed to the light analyzer so as to determine the nature of the specimen.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0017] These and other objects and features of the present disclosure will be more fully disclosed or rendered obvious by the following detailed description of the preferred embodiments, which is to be considered together with the accompanying drawings wherein like numbers refer to like parts and further wherein:

[0018] FIG. 1 is a schematic view of a novel Raman probe system;

[0019] FIG. 2 is a schematic view of selected elements of the Raman probe system;

[0020] FIG. 3 is a schematic view of the Raman probe system's laser subsystem, optical probe subsystem and spectrometer subsystem;

[0021] FIGS. 4-7 are schematic views of the optical control unit;

[0022] FIGS. 8-11 are schematic view of the Raman probe;

[0023] FIG. 12 is a schematic view showing the specimen being targeted through the probe;

[0024] FIG. 13 is a schematic view of the system controller;

[0025] FIGS. 14 and 15 are schematic views showing a standoff cone used in conjunction with the optical probe assembly.

**DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS**

[0026] Looking first at FIG. 1, there is shown a novel Raman probe system 5 for conducting remote sensing of a specimen 10. Novel Raman probe system 5 generally comprises a remote control robot 15 for piloting a remote Raman probe assembly 20 to a position adjacent to specimen 10, and a base station 25 for controlling operation of remote control robot 15 and for receiving specimen analysis information from remote Raman probe assembly 20.

[0027] Remote control robot 15 may be any remote control robot of the sort well known in the art of remote transport, remote sensing, remote bomb disposal, etc. By way of example but not limitation, remote control robot 15 may be a tracked vehicle remotely controlled by base station 25, e.g., by radio control of the sort well known in the art.

[0028] Looking now at FIGS. 1-3, remote Raman probe assembly 20 generally comprises a laser subsystem 30 (FIGS. 2 and 3) for generating the Raman pump signal, an optical probe subsystem 35 (FIG. 3) for delivering the Raman pump signal to the specimen and for gathering the Raman signature from the specimen, and a spectrometer subsystem 40 (FIGS. 2 and 3) for analyzing the Raman signature of the specimen so as to determine the nature of the specimen, and for transmitting analysis data to base station 25.

[0029] For convenience, laser subsystem 30 and spectrometer subsystem 40 may be packaged into an optical control unit 45 (see FIGS. 4-7) which is mounted onto remote control robot 15 so as to be carried thereby. Optical control unit 45 may also house an onboard power supply (e.g., a battery) for powering remote control robot 15 and its payload. Furthermore, optical control unit 45 is preferably provided with a communication subsystem 47 for permitting remote control robot 15, and its payload, to communicate with base station 25.

[0030] Optical probe subsystem 35 is also mounted to remote control robot 15. Preferably optical probe subsystem 35 is mounted to an articulating arm 50 (FIG. 1) on remote control robot 15. Articulating arm 50 may be remotely controlled by base station 25, such that the working end of optical probe subsystem 35 may be appropriately positioned adjacent to the specimen 10, as will hereinafter be disclosed.

[0031] Laser subsystem 30 may comprise any laser suitable for use in Raman spectroscopy. By way of example but not limitation, laser subsystem 30 may comprise one or more >300 mW, 785 nm semiconductor lasers with limited linewidths (e.g., about 2 cm.sup.-1). The output of laser subsystem 30 is delivered into the excitation fiber (see below) of optical probe subsystem 35 for delivery to the specimen.

[0032] Optical probe subsystem 35 is shown in FIGS. 3 and 8-11. Optical probe subsystem 35 comprises an excitation fiber 53 (e.g., 100 micrometer core diameter, Low OH) which delivers the excitation light through a flat polished excitation fiber ferule 54 (e.g., a 100 micrometer Core multimode fiber) and then through a laser collimating lens 54A (e.g., PCX, f=3 mm, D×3 mm) to a reflector 55 (e.g., for a 785 nm laser) and then to a notch filter 60 (e.g., OD>6) which also aligns the excitation light with the longitudinal axis of the Raman probe 65. The excitation light is then focused using focusing lens 70 (e.g., PCX, f=32 mm, D×3 mm) and then passed through a first pair of telescopic lenses 75, 80 (e.g., Achromat, f=19 mm, D=12.7 mm), a second pair of telescopic lenses 85, 90 (e.g., Achromat, f=45 mm, D×25 mm), and a window 95 for permitting the excitation light to pass out of the distal end of Raman probe 65 and onto specimen 10.

[0033] A shutter/wiper assembly 100 is disposed adjacent to window 95. Shutter/wiper assembly 100 is adapted to (i) selectively close off window 95 so as to protect the window (e.g., during storage and selected transit); and/or (ii) wiper off window 95 so as to keep it free of debris (e.g., during scanning in a dusty and/or debris-laden environment). Furthermore, shutter/wiper assembly 100 can be used to wipe away any of specimen 10 which might unintentionally stick to window 95, so as to help ensure that the specimen is not inadvertently carried away from the remote site by Raman probe system 5 at the conclusion of the analysis.

[0034] The excitation light from optical probe subsystem 35 engages specimen 10 and interacts with specimen 10 so as to produce the Raman signature of the specimen.

[0035] The light returning from specimen 10 (including but not limited to the Raman signature of the specimen) passes back through window 95, through lenses 90, 85 and then through lens 80. A beam splitter 105 (e.g., gold coated glass, 1.5.times.3.8 mm, 1 mm thick) then directs some of the returning light through an imaging lens 105A, through a CCD imaging lens aperture 106 (e.g., D×0.9 mm), through an infra red blocking filter 107 (e.g., to block 785 nm laser light and pass visible spectrum, OD>3) to CCD chip 108 on CCD active die 109 of CCD camera 110 driven by CCD electronics 115; and the remainder of the returning light (including the Raman signature of the specimen) is directed through lens 75, through focusing lens 70, through notch filters 60, 116 (e.g., OD>6), through a collection collimator lens 118 (e.g., PCX, f=4 mm, D×6 mm), through a flat polished collection fiber.
ferrule 119 (e.g., a 200 micrometer Core multimode fiber) and into collection fiber 120 (e.g., 200 micrometer core diameter, Low OH) for delivery to spectrometer subsystem 40. A shield 119A may be provided around CCD camera 110 for stray and laser light blocking.

Preferably, CCD camera 110 and CCD electronics 115 are constructed so as to provide streaming digital video output to base station 25. Preferably, CCD electronics 115 are contained in Raman probe 65 or, alternatively, some or all of CCD electronics 115 may be contained within optical control unit 45. In any case, CCD electronics 115 are carried by remote control robot 15.

The output from CCD camera 110 is relayed to base station 25, whereby to permit a user at base station 25 to aim the Raman pump light on specimen 10. More particularly, and looking now at FIG. 12, CCD camera 110 and base station 25 can be configured to overlay cross-hairs 125 on the image provided by CCD camera 110, whereby to permit the user to maneuver articulating arm 50 so that the Raman pump light is directed onto specimen 10.

Spectrometer subsystem 40 generally comprises a spectrometer 130 for identifying the wavelength characteristics of the Raman signature of specimen 10. Spectrometer subsystem 40 sends the wavelength characteristics of the Raman signature of specimen 10 to analysis apparatus 135, which determines the nature of specimen 10 using the wavelength characteristics of the Raman signature. If desired, spectrometer 130 may comprise a dispersive spectrometer having a resolution of 7-10.5 cm.sup.-1, a spectral range of 250-2800 cm.sup.-1, and 2048 pixels.

Thus it will be appreciated that specimen analysis is conducted completely onboard remote control robot 15, and only the analysis results need be communicated to base station 25. However, in one preferred form, it is preferred that remote control robot 15 be configured to send base station 25 the Raman signature spectra, as well as the analysis results.

Base station 25 preferably comprises a system controller 140, preferably including a computer having appropriate user interface controls (e.g., a joystick, touch pad, etc.) for (i) controlling the operation of remote control robot 15, including its articulating arm 50; (ii) receiving the output from CCD camera 110, whereby to permit remote aiming of Raman probe 65; and (iii) receiving the analysis results from analysis apparatus 135.

If desired, Raman probe assembly 20 and base station 25 may also be provided with a Raman feedback loop, whereby to use the relative intensity of the Raman signature being obtained by the system so as to further improve alignment of Raman probe 65 with specimen 10. More particularly, base station 25 is configured so as to measure (either continuously or on a periodic basis) how much useful Raman signal is being collected by the system. Then, using a feedback loop, the intensity of the Raman signal can be used, in conjunction with cross-hairs 125, to help guarantee that Raman probe 65 is properly aimed at specimen 10.

In one preferred form, some or all of the communication links between (i) remote controlled robot 15 and/or its payload (i.e., Raman probe assembly 20, including CCD camera 110 and CCD electronics 115) and (ii) base station 25, may be effected via Internet Web-based protocols, e.g., the IEEE 802.11b wireless network standard.

If desired, remote control robot 15 can communicate analysis results, Raman spectra or any other information (e.g., CCD camera pictures) to a location other than, or in addition to, base station 25.

Use

Raman probe system 5 is preferably used as follows.

First, the user interface controls at base station 25 are used to navigate remote control robot 15, including its articulating arm 50, to position Raman probe 65 adjacent to specimen 10, e.g., within approximately 1 to 2 inches.

Then, shutter/wiper 100 is opened, and CCD camera 110 and CCD electronics 115 are used, in conjunction with the cross-hairs 125, to move articulating arm 50 so that Raman probe 65 is aimed at specimen 10 and positioned approximately 30 mm away from the specimen.

Then the Raman signature feedback system is used to optimize positioning of Raman probe 65 relative to specimen 10. This is done by energizing laser subsystem 30 so that Raman pump light is directed at specimen 10 and reading the intensity of the Raman signature returned from specimen 10, with a feedback loop driving the positioning of articulating arm 50, so as to optimize the position of Raman probe 65 relative to the specimen, whereby to provide the best possible Raman signature for the specimen.

Then, laser subsystem 30 is energized so that the Raman pump light is directed at specimen 10. The return light is passed to spectrometer 130, so as to determine the Raman signature of the specimen, and then the Raman signature is fed to analysis apparatus 135 for determination of the nature of the specimen. Analysis apparatus 135 then sends information regarding the nature of specimen 10 (optionally including the Raman spectra for specimen 10 as well) to base station 25.

Further Constructions

If desired, various modifications can be made to the foregoing construction without departing from the scope of the present invention.

Thus, for example, and looking now at FIGS. 14 and 15, the shutter/wiper 100 may be replaced by a standoff cone 145. The standoff cone 145 can have various lengths, depending on whether specimen 10 is a solid or a liquid. More particularly, for solid specimens, standoff cone 145 is constructed so that when the distal tip of the standoff cone is positioned against the specimen, the focal point of the Raman laser will be located on the surface of the specimen. However, for liquid specimens, standoff cone 145 is constructed so that when the distal tip of the standoff cone is positioned against the specimen, the focal point of the Raman laser will be located on the within the body of the specimen.

It is to be understood that the present invention is by no means limited to the particular constructions herein disclosed and/or shown in the drawings, but also comprises any modifications or equivalents within the scope of the invention.

1-13. (canceled)
14. A Raman probe system comprising:
a base station;
a mobile robot remotely controllable from the base station;
a Raman probe assembly supported by the robot, the Raman probe assembly including a laser and a spectrometer,
a camera supported by the robot; and
a communication subsystem operable to communicate images from the camera and results from the Raman probe assembly to the base station.
15. The Raman probe system of claim 14, wherein the communication subsystem comprises a radio.
16. The Raman probe system of claim 14, wherein the communication subsystem comprises a radio.
17. The Raman probe system of claim 14, wherein the Raman probe assembly also includes an optical probe, the optical probe mounted to an articulating arm of the robot.
18. The Raman probe system of claim 14, wherein the Raman probe assembly also includes an analysis apparatus which receives wavelength characteristics of a Raman signature from the spectrometer.
19. The Raman probe system of claim 18, wherein the communication subsystem is operable to communicate results from the analysis apparatus to the base station.
20. The Raman probe system of claim 19, wherein the communication subsystem is operable to send the Raman signature to the base station.
21. The Raman probe system of claim 14, wherein the communication subsystem comprises a transmitter configured to transmit information using an Internet Web protocol.
22. The Raman probe system of claim 21, wherein the Internet Web protocol is IEEE 802.11b wireless network standards.
23. The Raman probe system of claim 14, wherein the Raman probe assembly comprises a standoff cone.
24. The Raman probe system of claim 23, when the standoff cone is constructed such that a distal tip is positioned at a focal point of the laser.
25. A Raman probe system comprising:
a mobile robot remotely controllable from a base station, the robot including a body and an articulated arm;
a camera supported by the robot;
a Raman probe assembly supported by the robot, the Raman probe assembly comprising:
an optical control assembly including a laser and a spectrometer, the optical control assembly mounted on the body of the robot; and
an optical probe mounted on the articulated arm of the robot; and
a wireless communication system operable to communicate images from the camera and results from the Raman probe assembly to the base station.
26. The Raman probe system of claim 25, wherein the Raman probe assembly also includes an analysis apparatus which receives wavelength characteristics of a Raman signature from the spectrometer.
27. The Raman probe system of claim 26, wherein the communication system is operable to communicate results from the analysis apparatus to the base station.
28. The Raman probe system of claim 27, wherein the communication system is operable to send the Raman signature to the base station.
29. The Raman probe system of claim 25, wherein the communication subsystem comprises a transmitter configured to transmit information using an Internet Web protocol.
30. The Raman probe system of claim 29, wherein the Internet Web protocol is IEEE 802.11b wireless network standards.
31. The Raman probe system of claim 25, wherein the Raman probe assembly comprises a standoff cone.
32. The Raman probe system of claim 31, when the standoff cone is constructed such that a distal tip is positioned at a focal point of the laser.
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