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(54) Title: TURBIDITY OPTICAL SENSOR FOR UNDERWATER CONTINUOUS IN-SITU MARINE OR FLUVIAL MONITORING

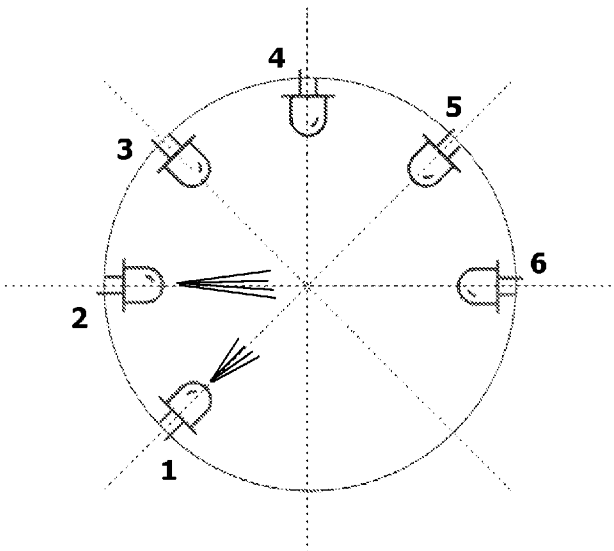

Fig. 1

(57) Abstract: Turbidity optical sensor for underwater continuous in-situ marine or fluvial monitoring, comprising: a support having a U-shaped cross-section defining a longitudinal flow channel which is laterally opened along said channel, said support comprising light emitters and receivers arranged around said channel, wherein said light emitters and receivers comprise an infrared emitter and three infrared receivers to measure transmitted, reflected and backscattered infrared light from said infrared emitter through said flow channel. Said support may be comprised of polymeric piece-wise joined planar plates, in particular joined at an angle of 45±10° between adjacent plates. Each plate may have a recess or bore for receiving one of said emitters or receivers. The support may be made of biodegradable compound, in particular polylactic acid, PLA. The support may be arranged to receive a curable resin, watertight after curing, such that the sensor is water-tight when placed underwater for in- situ marine or fluvial monitoring.

WO 2019/186366 A1

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DESCRIPTION

TURBIDITY OPTICAL SENSOR FOR UNDERWATER CONTINUOUS IN-SITU MARINE OR FLUVIAL MONITORING

Technical field

[0001] The present disclosure relates to a turbidity optical sensor for continuous in-situ marine or fluvial monitoring. In particular, the disclosure is related to the methods and optical devices to measure turbidity in liquids in real environment conditions, more specifically for continuous monitoring in marine or fluvial environments.

Background

[0002] Turbidity is a physical property of fluids that translates into reduced optical transparency due to the presence of suspended materials that block the transmission of light. These materials can be of organic or inorganic origin, varying in colour, matter and size, ranging from macroscopic to colloidal particles.

[0003] Turbidity is not a physical quantity so it is not directly measurable. The complexity of interactions between the optical properties of suspended materials such as colours and sizes; the characteristics of the fluid, especially its index of refraction, colour and properties of the solutes; the wavelength and intensity of the incident light, turn the turbidity as a visual property quite subjective. Therefore, turbidity as an optical property of water becomes one of the most difficult parameters to measure.

[0004] The first practical attempt to measure turbidity in-lab was through the Jackson candle method. Developed over a century ago, this instrument consists of a lighted candle placed under a glass tube with a flat bottom. The fluid in which the turbidity is to be measured is slowly poured into the tube until the flame image is no longer visible from a top point of view (the light does not disappear completely, just the flame image). This phenomenon occurs when the light is completely dispersed by the particles suspended in the liquid. The tube contains a graduation that allows to relate the volume of the liquid to its transparency and consequent turbidity.

[0005] Other turbidimeters based on the extinction of light were developed. Among these, the most recognized and still used today in naval instruction, is the disc of Secchi, created in 1865 by Pietro Angelo Secchi.

[0006] The Secchi disk consists of a flat circular disk with a diameter between 16cm and 40cm, usually divided into four equivalent parts with the contrasts of black and white or, in some cases, completely black or completely white. This disc, attached by a rope, is submerged slowly in the water until it is no longer visible, finding the Secchi depth (usually in meters or centimetres). Greater depths are related to high clarity of water and low levels of turbidity. In the opposite, smaller depths indicate high levels of turbidity.

[0007] Even though it is a widely used method it is also unreliable. Readings are affected by changes in sunlight conditions, water shaking, time of day, and human error. Currently, these types of light-extinction methods are considered obsolete, in favour of electronic instruments that offer greater dynamic range and accuracy.

[0008] The optical turbidimeters have solved the problem of susceptibility to human error presented by previous methods. These types of devices use a light source and one or more optical receivers. When the light passes through the medium it will be dispersed and absorbed by the existing suspended particles, varying the electrical signal of the receivers. This electrical value may be related to the turbidity.

[0009] Currently, there are some standardized methods for measuring turbidity, however, each measurement method uses a different unit. A multiplicity of turbidity units has been introduced because a change in the design, type of light source, detector or measuring angle will change the sensor reading. Thus, different turbidity instruments can produce several measurements in the same sample.

[0010] There are several standard water quality standard methods in use. The US Environmental Protection Agency (EPA) has approved eight standards for monitoring drinking water. Until 2009, only four methods were accepted: EPA Method 180.1, Standard Method 2130B, Great Lakes Instrument Method 2 (GLI 2) and Hach Method. In 2009, USEPA approved four new methods: Mitchell Methods M527 and M5331, Orion AQ4500, and AMI Turbiwell. In addition to these, the United States Geological Survey also uses other methods, such as the International Organization for Standardization (ISO) 7027. All those methods are used in water treatment plants for human consumption, offering a high accuracy for low turbidity values. For marine or river environments, where turbidity can have higher values, these devices become dysfunctional, not only because of their low dynamic range, but also because most are laboratory devices, making them large, expensive, and dependent of the electrical grid.

[0011] Some turbidity sensors for continuous monitoring were developed for continuous monitoring in the last decades. Most of them are optical devices but only uses one type of detection, becoming specific for a strict type of environment and do not have the flexibility to adapt to other contexts.

[0012] The Patent US 6842243 - "Turbidity sensor" relates to a reduced size sensor for in situ monitoring, however it only uses nephelometric technology. In the same way, US 4841157 – “Optical backscatter turbidity sensor” discloses an optical turbidimeter with multiple detectors, however, it also uses one type of optical detection (backscattering).

[0013] The Patent US 8654319 - "Chlorophyll and turbidity sensor system" relates to a low-cost sensor for measuring chlorophyll and turbidity concentration through three photodetectors. This sensor uses blue light, and detectors measure fluorescence, due to optical filters. Only transmitted light detection is used for turbidity, and the patent describes only the measurement of chlorophyll. Proof of this is that the light source used is a LED of preferably 660nm, 525nm or 470nm, wavelengths susceptible to fluorescence of organic matter, thus inadequate for turbidity measurements. For accurate turbidity measurement, infrared light must be used, since it is less susceptible to particle coloration and does not interfere with the organic matter photosynthesis.

[0014] Another example of turbidity and fluorescence sensor is the Patent CN 2844902 – “Composite probe for underwater fluorimeter and turbidimeter”. It also intends to measure fluorescence and turbidity using a 430nm and 850nm emitting source, but only includes the nephelometric detection.

[0015] Summing up, the presented patent documents do not incorporate in their design a conjugation that allows to make the nephelometric, backscattering and transmitted light detections, becoming accurate for high or for low turbidity values, and not having the flexibility in dynamic range and precision for all type of environments, in particular marine or fluvial environments.

[0016] These facts are disclosed in order to illustrate the technical problem addressed by the present disclosure.

General Description

[0017] A turbidity optical sensor for continuous in situ monitoring was developed for marine or fluvial applications. The sensor uses an infrared LED and three infrared photodetectors with three different positions related to the light source - in particular 45º, 90º and 180º - resulting in three different types of light detection: backscattering, nephelometry and transmitted light, respectively. This design allows monitoring in practically any type of water environment, offering a wide dynamic range and accuracy for the detection of the amount of sediment suspended in water based on turbidity values. This apparatus was designed in particular to detect particles from clay to sand sizes (from <2 micrometres to 2 mm). An ultraviolet emitter-receiver pair is also used to differentiate organic and inorganic matter through the different types of matter responses at different wavelengths. The optical transducers are built in a preferably watertight structure with detectors in a radial configuration where a printed circuit board with the electronic signal coupling is assembled.

[0018] The present invention consists on a new turbidity measurement device for continuous monitoring of the amount of suspended material that circulates in maritime and fluvial environments.

[0019] The measurement is possible through the illumination of the sample, where the light is absorbed, reflected and dispersed by the particles in suspension. This optical variation is sensed by a set of receivers that do the optical-electrical transduction. With the increasing of suspended sediments in the sample, and consequent turbidity, the electrical output value of the photodetectors will increase or decrease by the position in which they are placed relative to the light source.

[0020] An infrared light source (e.g. 940nm LED) and three receivers of the same wavelength are used (e.g. IR phototransistors). The optical transducers are placed in a radial configuration, obtaining three different types of detection: nephelometric (detector at 90º in relation to the emitter with variation of ± 10º), backscatter (detector at 45º in relation to the emitter with variation of ± 20º) and transmitted light (detector at 180º to the emitter with variation of ± 10º), thus obtaining a flexibility in both dynamic range and precision and providing the sensor the ability to monitor in any type of water environment.

[0021] An ultraviolet light source (e.g. 380nm LED) and a transmitted light receiver of the same wavelength (e.g. phototransistors) are also used to, together with the infrared transmitted light detection, obtain a differential value and estimate the amount of organic and inorganic matter. This distinction is possible due to the different behaviour of different types of matter in relation to different wavelengths: organic matter is susceptible to absorb smaller wavelengths, performing the photosynthesis, while inorganic matter is more prone to absorb longer wavelengths, such as infrared.

[0022] The optical transducers are assembled in a watertight structure that protects the electronics from the water and allow its submersion. A printed circuit board with the electrical signal coupling is also embedded in the structure, as close as possible to the receivers, to minimize leakages in the signal transmission.

[0023] The electrical output of the sensor is composed of four DC signals, corresponding to the four photoreceivers. The output signals and power supply have their connection between the printed circuit board and the outside of the sensor through a network cable that can be connected to an external device, such as a microcontroller or a data logger.

[0024] The microcontroller computes the turbidity value, using the implemented algorithm, and also computes the composition, as a percentage of organic / inorganic matter.

[0025] It is disclosed a turbidity sensor for underwater measurement, comprising a watertight housing with a shape that defines a flow-through area that is open to the environment and through which a liquid can flow through.

[0026] An embodiment comprises an infrared light source that illuminates the sample and at least three infrared photoreceivers to measure the incident light, wherein the light source and the photoreceivers are positioned in the housing around the flow-through cell such that light from the light source propagates into the flow-through area.

[0027] An embodiment comprises at least one infrared photoreceiver placed at 45±20º relative to the infrared light source to measure backscatter light from the suspended sediments in the sample.

[0028] An embodiment comprises at least one infrared photoreceiver placed at 90±10º relative to the infrared light source to measure diffracted light from the suspended particles in the sample.

[0029] An embodiment comprises at least one infrared photoreceiver placed at 180±10º relative to the infrared light source to measure non-absorbed light from the suspended particles in the sample.

[0030] An embodiment comprises an ultraviolet light source and at least one ultraviolet photoreceiver to measure the incident light, wherein the light source and the photoreceivers are positioned in the housing around the flow-through cell such that light from the light source propagates into the flow-through area.

[0031] An embodiment comprises at least one ultraviolet photoreceiver placed at 180±10º relative to the ultraviolet light source to measure non-absorbed light from the suspended particles in the sample.

[0032] An embodiment comprises a printed circuit board, assembled in the sensor housing, with the electronic instrumentation relative to the photoreceivers and light sources actuation.

[0033] It is described a turbidity optical sensor for underwater continuous in-situ marine or fluvial monitoring, comprising:

a support having a U-shaped cross-section defining a longitudinal flow channel which is laterally opened along said channel, and

light emitters and receivers arranged around said channel;

wherein said light emitters and receivers comprise:

an infrared emitter, and

three infrared receivers to measure respectively transmitted, reflected and backscattered infrared light from said infrared emitter through said flow channel.

[0034] The open channel (by way of the U-shaped cross-section) allows measuring the water at its most natural state, avoiding pressures or eddies that would distort the measurements, which would be the case for example from a more enclosed measurement channel.

[0035] In an embodiment, said support is comprised of polymeric piece-wise joined planar plates.

[0036] In an embodiment, said piece-wise planar plates are joined between adjacent plates.

[0037] In an embodiment, said piece-wise planar plates are joined at an angle of 45±10° between adjacent plates.

[0038] In an embodiment, each said planar plate has a recess for receiving one of each of said emitters or receivers, in particular said recess being a bore located centrally in each said plate.

[0039] An embodiment comprises a polymeric reinforcement structure backing said planar plates.

[0040] In an embodiment, said reinforcement structure comprises reinforcement ribs along said planar plates.

[0041] In an embodiment, the support is made of biodegradable compound.

[0042] In an embodiment, the support is made of polylactic acid, PLA.

[0043] In an embodiment, the support is arranged to receive a curable resin, said resin being water-tight after curing, such that the sensor is water-tight when placed underwater for in-situ marine or fluvial monitoring.

[0044] In an embodiment, the inner surface around said channel is of black colour to minimize fortuitous light reflections.

[0045] In an embodiment, the infrared emitter and the infrared receiver to measure backscattered infrared light from said infrared emitter are arranged at an angle of 45±10° around said channel.

[0046] In an embodiment, the infrared emitter and the infrared receiver to measure reflected infrared light from said infrared emitter are arranged at an angle of 90±10° around said channel.

[0047] In an embodiment, the infrared emitter and the infrared receiver to measure transmitted infrared light from said infrared emitter are arranged at an angle of 180±10° around said channel.

[0048] Turbidity sensor according to the previous claim further comprising an ultraviolet emitter and an ultraviolet receiver to measure transmitted ultraviolet light from said ultraviolet emitter through said flow channel.

[0049] Turbidity sensor according to the previous claim wherein the ultraviolet emitter and the ultraviolet receiver to measure transmitted ultraviolet light from said ultraviolet emitter are arranged at an angle of 180±10º around said channel.

[0050] An embodiment comprises an electronic circuit assembled within said support, said circuit comprising electronics for operating said emitters and receivers.

[0051] An embodiment comprises a data processor configured to distinguish organic matter turbidity from inorganic matter turbidity by differentiating the measured transmitted infrared light from the measured transmitted ultraviolet light.

Brief Description of the Drawings

[0052] The following figures provide preferred embodiments for illustrating the disclosure and should not be seen as limiting the scope of invention.

[0053] **Figure 1:** Schematic representation of an embodiment of the transducer's positions design.

[0054] **Figure 2:** Schematic of representation of an embodiment of the sensor structure design.

[0055] **Figure 3:** Schematic of representation of an embodiment of the hardware of the sensor.

Detailed Description

[0056] The operation of the sensor consists on interaction between the incident light and the suspended matter present in the water that passes freely through the central part of the apparatus. The presence of suspended particles will act as optical obstacles that will absorb, reflect and diffract the incident light, modifying its original path and power. With the variation of the photodetectors light sensed, it becomes possible to establish a relationship between the instant sampled turbidity and the amount of suspended material.

[0057] **Figure 1** shows a schematic of the transducers positions design. Different receptors' positions relative to the light source provides different electrical responses. An infrared light source (2) and three optical receivers of the same wavelength (3), (4) and (6) are used, obtaining the backscatter, nephelometric and transmitted light detections, respectively. An ultraviolet emitter-receiver pair for transmitted light detection, (1) and (5), is also used for the differentiation between organic and inorganic matter.

[0058] As light emitting source is used a 940nm infrared LED, **Figure 1 (2)**, due to its low cost and great commercial offer. In addition, compared to their competitors (lasers and lamps), it has a much faster response than lamps, allowing light to be pulsed at high frequencies, and do not present major maintenance or calibration problems as lasers. The use of infrared wavelength results in less susceptibility to the coloration of the particles in the medium and is outside of the optical absorption band of the organic matter to perform the photosynthesis (typically ultraviolet, green and blue). These two properties make the infrared more robust and adaptable to different environments characteristics.

[0059] For the optical detection and optical-electric transduction, three infrared wavelength sensitive phototransistors, **Figure 1 (3), (4) and (6)**, are used, with different positions in relation to the light source. This configuration results in three types of optical detection: backscatter, nephelometric and transmitted light.

[0060] In the backscattering light detection technique, the optical receiver **Figure 1 (3)** is placed at 45º to the light source **Figure 1 (2)** and senses the reflected light back from the particles suspended in the fluid. For purely distilled water this type of detection has a zero-optical sensing value (there are no obstacles to reflect the light), and with increasing turbidity and consequent increase of suspended particles and reflections, the detected light output will increase. The advantage of this type of detection is the wide measuring range and accuracy for high turbidity values. In the other hand, for low turbidity values it is not as accurate as nephelometric detection and is the less sensitive of all technologies. The backscatter detection strongly depends on the size, composition and shape of the suspended particles.

[0061] The nephelometric detection measures the diffracted light at 90º, **Figure 1 (4)**, relative to the light source **Figure 1 (2)**. As the backscatter technique, for distilled water, the absence of optical obstacles results in a null optical value, which will increase with the increase of suspended particles. However, for high turbidity values the diffracted light will also be absorbed by the particles and the light output will decrease. The nephelometric detection is particularly accurate for low turbidity but not useful for high values, where its sensitivity is low. The nephelometric technique depends mostly on the size and number of particles in suspension.

[0062] The transmitted light detection is the measurement is related to the absorbance of the light and uses an optical detector at 180º relative to the light source, **Figure 1 (6) and (2)**, respectively. For distilled water, the detector has the maximum output value that will decrease with the increase of turbidity (particles will absorb and scatter the light on its path). This technique presents the higher sensitivity, offering a wide dynamic range. In the other hand, it is very vulnerable to the coloration and particles size which results in a lower precision.

[0063] By last, an ultraviolet emitter, **Figure 1 (1)**, and an ultraviolet transmitted light detector, **Figure 1 (5)**, are also used to, in complement with the infrared transmitted light detector, to distinguish organic from inorganic matter. This measurement is possible due to the different behaviour of different types of matter in relation to different wavelengths: organic matter is more susceptible to smaller wavelengths, having a high absorption ratio of ultraviolet radiation, whereas inorganic matter is more susceptible to longer wavelengths, such as infrared. Considering this, using the absorption values of infrared and ultraviolet transmitted light detectors, makes this discrimination possible.

[0064] **Figure 2** shows a sensor structure design with a radial configuration to place the transducers. The final model is built in PLA, using 3D printing, and filled with epoxy for submersion.

[0065] The sensor structure, **Figure 2**, was built with a radial configuration, in a 3D printer, to assemble the transducers in the respective positions. The structural material is polylactic acid (PLA), a biodegradable maize-based compound, not harmful to aquatic ecosystems. For the watertight needs, the sensor has its interior filled with epoxy resin, protecting the electronics from water infiltration. The sensor walls, where the LEDs are placed, are painted with opaque black acrylic painting to minimize undesired light reflections.

[0066] **Figure 3** shows a hardware schematic of the sensor. A printed circuit board with the electronic instrumentation was developed to be assembled in the sensor structure. Each photodetector has a current to volt converter and a buffer amplifier resulting in four DC outputs. This output can be read by a ADC external to the sensor and processed by a microcontroller or data logger.

[0067] A small size (2,5x1,5cm) printed circuit board with the electronic instrumentation, **Figure 3**, was designed to be assembled in the sensor structure, close to the optical receivers. Each photodetector has a current to voltage converter and a buffer amplifier that allows the reduction of leakage currents through the transmission cables.

[0068] The sensor presents four dc outputs - backscatter, nephelometric and IR and UV transmitted light detectors - two input controllers for the IR and UV LEDs and the power supply. It is connected to a microcontroller to compute turbidity and organic content.

[0069] The developed device results in a turbidity sensor with the necessary characteristics for a continuous monitoring in situ in oceanic and fluvial applications, where large turbidity variations are expected, and differentiation between organic and inorganic matter is relevant. Its configuration results in a high flexibility to adapt to every environment characteristics, using the different detections typologies for an accurate measurement.

[0070] The term "comprising" whenever used in this document is intended to indicate the presence of stated features, integers, steps, components, but not to preclude the presence or addition of one or more other features, integers, steps, components or groups thereof.

[0071] The disclosure should not be seen in any way restricted to the embodiments described and a person with ordinary skill in the art will foresee many possibilities to modifications thereof.

[0072] The above described embodiments are combinable.

[0073] The following claims further set out particular embodiments of the disclosure.

CLAIMS

1. Turbidity optical sensor for underwater continuous in-situ marine or fluvial monitoring, comprising:
   a support having a U-shaped cross-section defining a longitudinal flow channel which is laterally opened along said channel, and
   light emitters and receivers arranged around said channel;
   wherein said light emitters and receivers comprise:
   an infrared emitter, and
   three infrared receivers to measure respectively transmitted, reflected and backscattered infrared light from said infrared emitter through said flow channel.

2. Turbidity sensor according to the previous claim wherein said support is comprised of polymeric piece-wise joined planar plates.

3. Turbidity sensor according to the previous claim wherein said piece-wise planar plates are joined between adjacent plates.

4. Turbidity sensor according to the previous claim wherein said piece-wise planar plates are joined at an angle of 45±10° between adjacent plates.

5. Turbidity sensor according to any of the claims 2-4 wherein each said planar plate has a recess for receiving one of each of said emitters or receivers, in particular said recess being a bore located centrally in each said plate.

6. Turbidity sensor according to any of the claims 2-5 further comprising a polymeric reinforcement structure backing said planar plates.

7. Turbidity sensor according to the previous claim wherein said reinforcement structure comprises reinforcement ribs along said planar plates.

8. Turbidity sensor according to any of the previous claims wherein the support is made of biodegradable compound.

9. Turbidity sensor according to the previous claim wherein the support is made of polylactic acid, PLA.

10. Turbidity sensor according to any of the previous claims wherein the support is arranged to receive a curable resin, said resin being water-tight after curing, such that the sensor is water-tight when placed underwater for in-situ marine or fluvial monitoring.

11. Turbidity sensor according to any of the previous claims wherein the inner surface around said channel is of black colour to minimize fortuitous light reflections.

12. Turbidity sensor according to any of the previous claims wherein the infrared emitter and the infrared receiver to measure backscattered infrared light from said infrared emitter are arranged at an angle of 45±10° around said channel.

13. Turbidity sensor according to any of the previous claims wherein the infrared emitter and the infrared receiver to measure reflected infrared light from said infrared emitter are arranged at an angle of 90±10° around said channel.

14. Turbidity sensor according to any of the previous claims wherein the infrared emitter and the infrared receiver to measure transmitted infrared light from said infrared emitter are arranged at an angle of 180±10° around said channel.

15. Turbidity sensor according to the previous claim further comprising an ultraviolet emitter and an ultraviolet receiver to measure transmitted ultraviolet light from said ultraviolet emitter through said flow channel.

16. Turbidity sensor according to the previous claim wherein the ultraviolet emitter and the ultraviolet receiver to measure transmitted ultraviolet light from said ultraviolet emitter are arranged at an angle of 180±10º around said channel.

17. Turbidity sensor according to any of the previous claims comprising an electronic circuit assembled within said support, said circuit comprising electronics for operating said emitters and receivers.

18. Turbidity sensor according to any of the previous claims comprising a data processor configured to distinguish organic matter turbidity from inorganic matter turbidity by differentiating the measured transmitted infrared light from the measured transmitted ultraviolet light.

D R A W I N G S

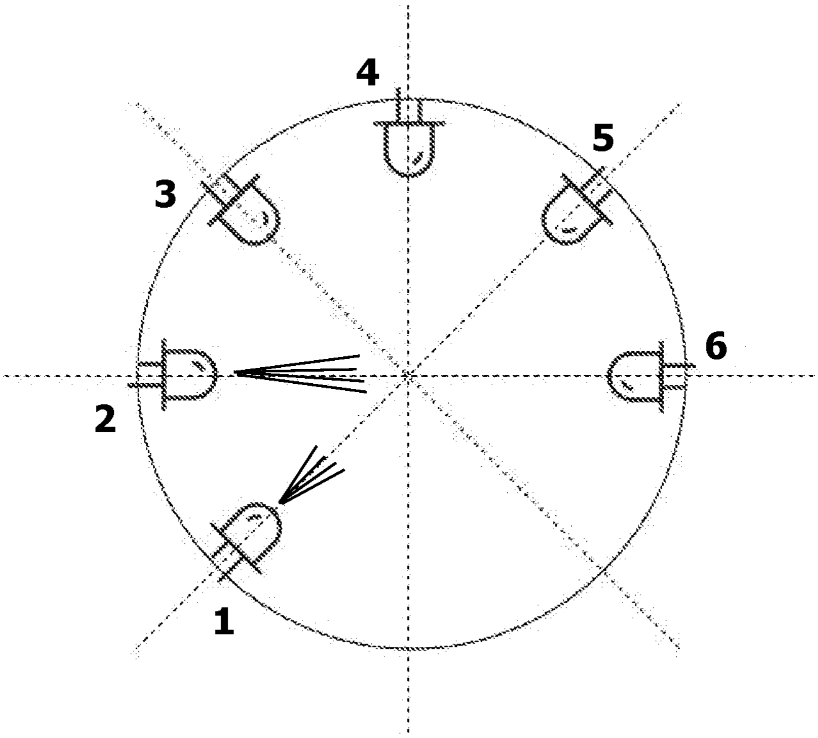


Fig. 1

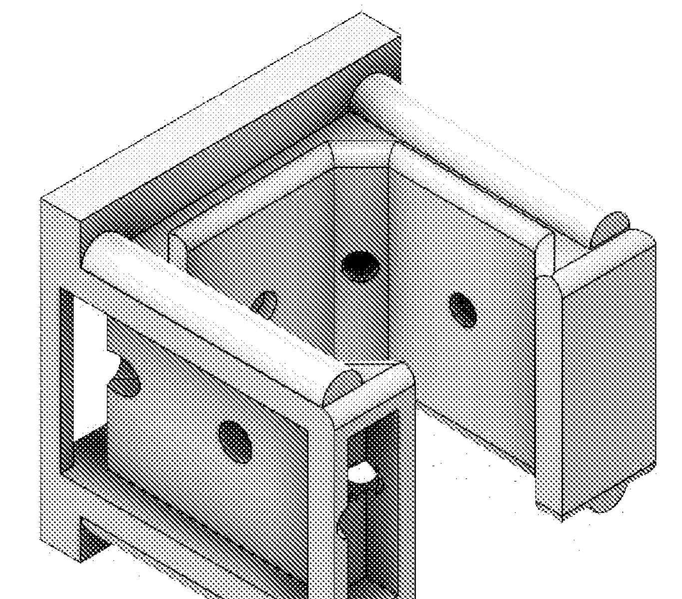
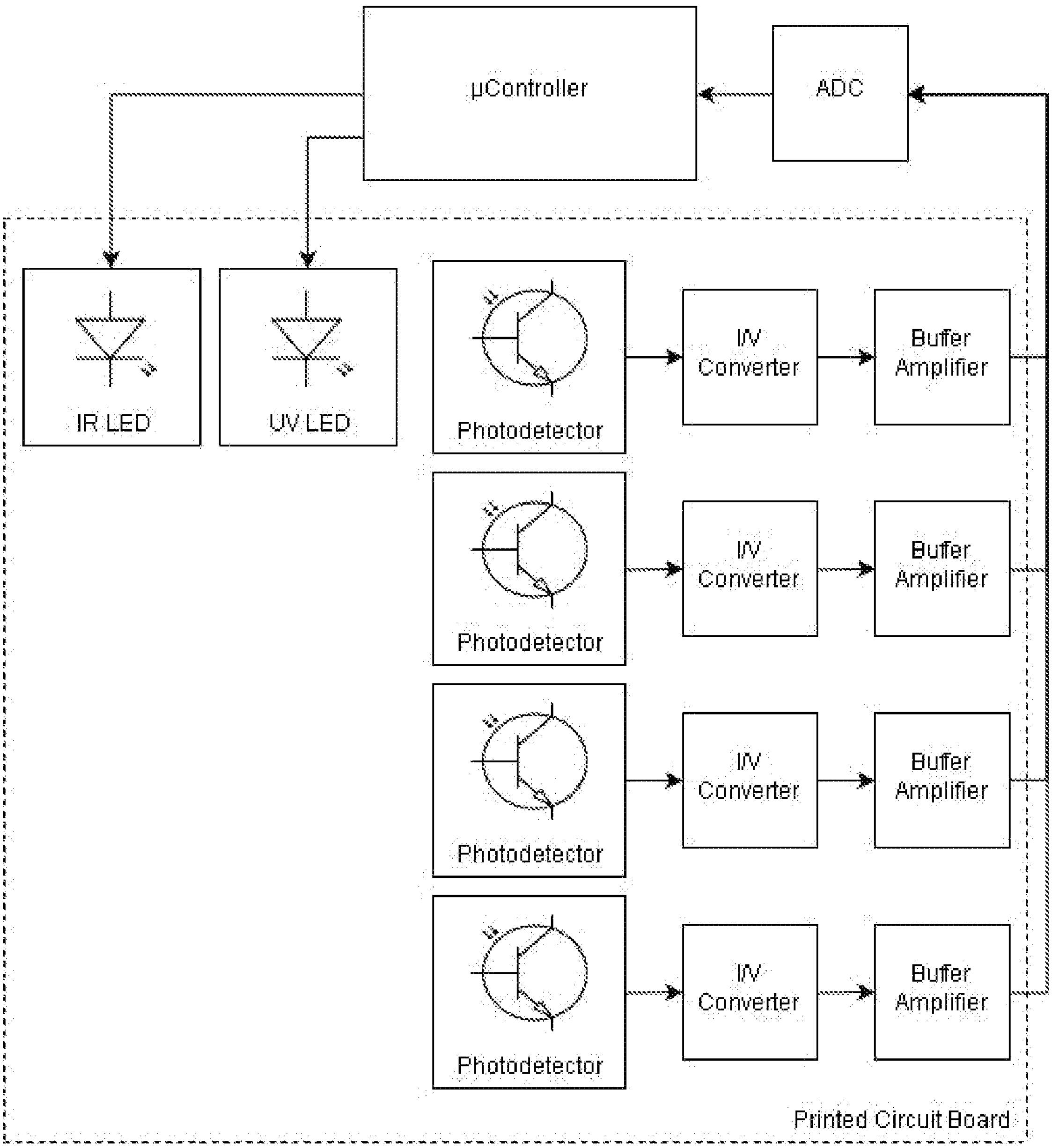


Fig. 2


µController
ADC
IR LED
UV LED
Photodetector
I/V Converter
Buffer Amplifier
Photodetector
I/V Converter
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Photodetector
I/V Converter
Buffer Amplifier
Photodetector
I/V Converter
Buffer Amplifier
Printed Circuit Board

Fig. 3

INTERNATIONAL SEARCH REPORT

International application No
PCT/IB2019/052402

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01N33/18 G01N21/35 G01N21/53 G01N21/47 G01N21/33
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01N

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

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 6 464 798 B1 (ROSENBAUER MICHAEL [DE] ET AL) 15 October 2002 (2002-10-15) abstract; figures 2-4 column 1, lines 24-36 column 12, line 21 - column 13, line 27 -----	1,8,9, 13-17 2-7, 10-12,18
Y	WO 2014/195946 A1 (BLUE I WATER TECHNOLOGIES LTD [IL]) 11 December 2014 (2014-12-11) pages 3-5 -----	12
Y	WO 02/068940 A1 (HONEYWELL INT INC [US]) 6 September 2002 (2002-09-06) figure 12 column 13, lines 10-15 -----	2-7,11

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
9 July 2019	22/07/2019

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1

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