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Modern large-scale civil engineering such as bridges, tunnels, space shuttles, large dams, and other infrastructure facilities have significant applications. These facilities not only require huge economic investment in the manufacturing process but also are closely related to personal safety. The facilities' service life is usually decades or even hundreds of years [1,2]. In the course of using, they could inevitably be coupled with various disasters (such as environmental loads, fatigue effects, etc.). The structure could appear in different degrees and different kinds of damage

MONITORING USING FIBER BRAGG GRID SENSORS IN EMERGENCY PREVENTION OF BRIDGES

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ABSTRACT

In recent years, with the development of materials science and architectural art, ensuring the safety of modern buildings is the top priority while they are developing toward higher, lighter, and more unique trends. Structural health monitoring (SHM) is currently an extremely effective and vital safeguard measure. Because of the fiber-optic sensor's (FOS) inherent distinctive advantages (such as small size, lightweight, immunity to electromagnetic interference (EMI) and corrosion, and embedding capability), a significant number of innovative sensing systems have been exploited in the civil engineering for SHM used in projects (including buildings, bridges, tunnels, etc.). The purpose of this review article is devoted to presenting a summary of the basic principles of various fiber-optic sensors, classification and principles of FOS, typical and functional fiber-optic sensors (FOSs), and the practical application status of the FOS technology in SHM of civil infrastructure.

[3,4], which may cause serious personal accidents and property losses. Therefore, whether these structures can work safely for a long time has attracted lots of attention. It is necessary to carry out real-time health monitoring and evaluation of engineering structures to put an end to the potential hazards and improve the safety performance of civil facilities.

The field of fiber optics has undergone tremendous growth and advancement over the last 25 years. The fiber optic communication industry has literally revolutionized the telecommunication

industry by providing higher performance, more reliable telecommunication links with ever decreasing bandwidth cost. This revolution is bringing about the benefits of high volume production to component users and a true information superhighway built of glass. Developments fiber optic sensor [2,3] technology has been a major user of technology associated with the optoelectronic and fiber optic communication industry. Since the past decades, various devices, including fiber optic gyroscopes; sensors of temperature, pressure, and vibration; and chemical probes has been under development of Fiber optic sensors (FOS) technology. FOS offer a number of advantages, such as increased sensitivity compared to existing techniques and geometric versatility, which permits into arbitrary shapes.

The ability of fiber optic sensors has been enhanced to substitute traditional sensors for acoustics, vibration, electric and magnetic field measurement, acceleration,

rotation, temperature, pressure, linear and angular position, strain, humidity, viscosity, chemical measurements and a host of other sensor applications. They can be used in high voltage, high temperature, or corrosive environments due to its dielectric property; In addition, these sensors are compatible with communications systems and have the capacity to carry out remote sensing. Recently, investigation in the field has focused on the development of new materials with non-linear optical properties for important potential applications in photonics. Examples of these materials are the conjugated semiconducting polymers that combine optical properties with the electronic properties of semiconductors. In addition, these conducting polymers have photo luminescent and electroluminescent properties, making them attractive for applications in optoelectronics [7].

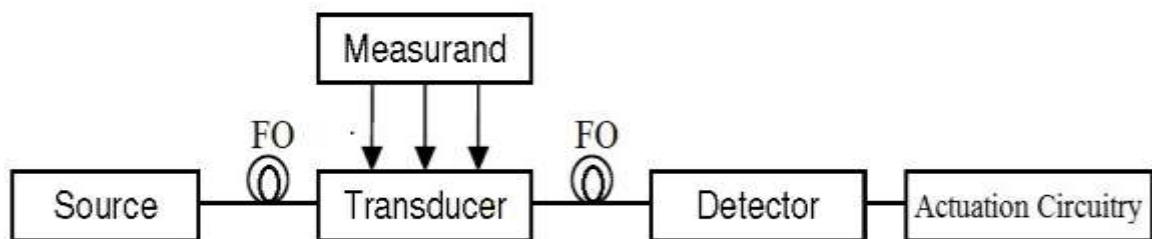


Figure 1. Optical fiber sensor system basic components.

Fiber optic sensor technology in turn has often been driven by the development and subsequent mass production of components to support these industries. The inherent advantages of fiber optic sensors which include their ability to be lightweight, of very small size, passive, low attenuation, and low power, immunity to electromagnetic interference (EMI), high sensitivity, wide bandwidth and environmental ruggedness were heavily used to offset their major disadvantages of

high cost and unfamiliarity to the end user[6][9].

Optical Fiber Sensors Advantages Over Traditional Sensors. The advances in research and development of FOS devices has extended their applications to various fields of technology, such as medical, chemical, and telecommunications industries. They have been developed to work on a wide variety of physical properties, like temperature, chemical changes, electric and magnetic fields,



vibrations, strain, displacement (position), flow, pressure, rotation, radiation, liquid level, light intensity, and colour. For performance in harsh environments, FOS proves reliable and rigid sensing devices over conventional electrical and electronic sensors where they have difficulties [1][6][7]. Contrary, optical fiber sensors exhibit a number of advantages over other types of sensors; they are;

- Enable small sensor sizes
- Are non-electrical devices
- Offer sensitivity to multiple environmental parameters
 - Require small cable sizes and weights
 - Permit remote sensing
 - Allow access into normally inaccessible areas
 - Often do not require contact
 - Immune to radio frequency interference (RFI) and electromagnetic interference (EMI)
 - Do not contaminate their surroundings and are not subject to corrosion
 - Provide high sensitivity, resolution and dynamic range
 - Can be interfaced with data communication systems

Classification and Principles of Fiber-Optic Sensor (FOS). The working process of the optical fiber sensor includes but not limited to the monitoring of external factors and signal transmission. When light propagates in an optical fiber, characteristic parameters such as light intensity, phase, polarization state, wavelength, or frequency will change. Therefore, FOS can be divided into intensity-modulated FOS, phase modulated FOS, polarization modulated FOS, and frequency

modulated FOS. In the FOS system, the modulation occurs inside the optical fiber when the light in the optical fiber is transmitted from the light source to the detector, called the intrinsic FOS. The modulation that occurs outside the optical fiber called extrinsic FOS. FOS can be divided into interferential FOS and non-interferential FOS according to whether the light interferes or not. In addition, according to the induction range, FOS can be divided into point (local) FOS, quasi-distributed FOS, and distributed FOS. The most commonly used in civil infrastructure are Fabry-Perot fiber-optic sensor (FPFOS) [8,9], fiber Bragg grating (FBG) sensor [10,11], optical time domain reflectometer (OTDR) [12,13], and long-period fiber grating (LPFG) sensor [13,14].

Fabry-Perot Fiber-Optic Sensor. The optical fiber sensors utilize the change of optical phase affected by the physical field to reflect the properties of the measured objects. After being emitted by the light source, the light is divided into two beams with the same frequency, polarization direction, and initial phase through the prism. One beam is signal light and the other beam is reference light. Interference occurs when they meet. The interference image can be used to infer the influence of external factors on the signal light. Interferometric FOS can be divided into Michelson FOS, Mach-Zehnder FOS, Sagnac FOS, and Fabry-Perot FOS. The schematic diagram of the Fabry-Perot interference cavity is shown in Figure 2. We mainly introduce the FPFOS in this review.

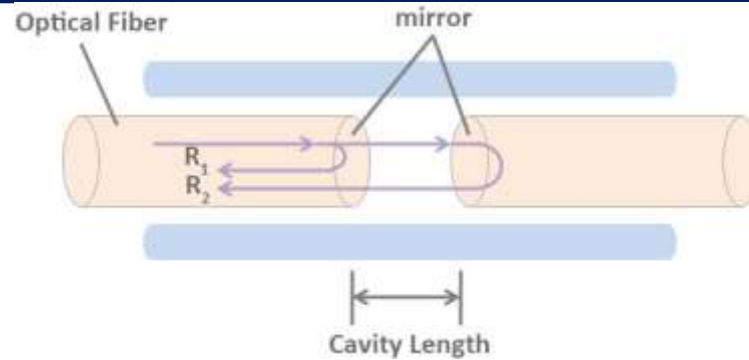


Figure 2. Schematic diagram of Fabry-Perot interference cavity.

The core of the FPFOS is the interference cavity. According to the different structure of interference cavity, FPFOS can be divided into intrinsic type and non-intrinsic type. In the intrinsic Fabry-Perot interferometric (IFPI) sensing system, the interference cavity is generally composed of a single-mode fiber-optic and an insulated mirror, and the end face of the fiber-optic cut by the fiber-optic can also be used as a mirror. In the extrinsic Fabry-Perot interferometric (EFPI) sensing system, the interference cavity is composed of air or other non-fiber optic solid media. The light source can use either a He-Ne laser or a low coherence light source to form interference after entering the optical Fabry-Perot cavity. The above two types of Fabry-Perot FOSs make use of the physical parameters to be measured to cause the change of phase difference, so that the optical path difference is changed, and then the interference signal through the detector is transformed into electrical signal for processing. According to the change of coherent optical phase difference, the change of physical parameters to be measured can be obtained.

Fiber Bragg Grating Sensor. SHM is the most active field in the application of FBG sensors. The low

manufacturing cost, high-quality demodulation system, and practical packaging technology are important factors for the wide application of FBG sensors. FBG sensors can be attached to the surface of the structure or embedded in the structure to achieve real-time monitoring of the structure and monitor the formation of structural defects. Besides, a large number of FBG sensors can be connected in series to form a sensor network system, and the sensing signals can be remotely accessed to the central monitoring room for analysis and processing.

Intrinsic fiber optic sensor (IFOS): the intensity, phase, polarization, wavelength or transit time of light can be modulated. Sensors which modulate light intensity tend to use mainly multimode fibers, while only mono mode cables are used to modulate other parameters. An interesting feature of IFOSs is that they can provide distributed sensing over distances of up to 1 meter. In Intrinsic sensors, the variable of interest (physical perturbation) must modify the characteristics of the optical fiber to modify the properties of the light carried by the fiber, figure 3 (Intrinsic)

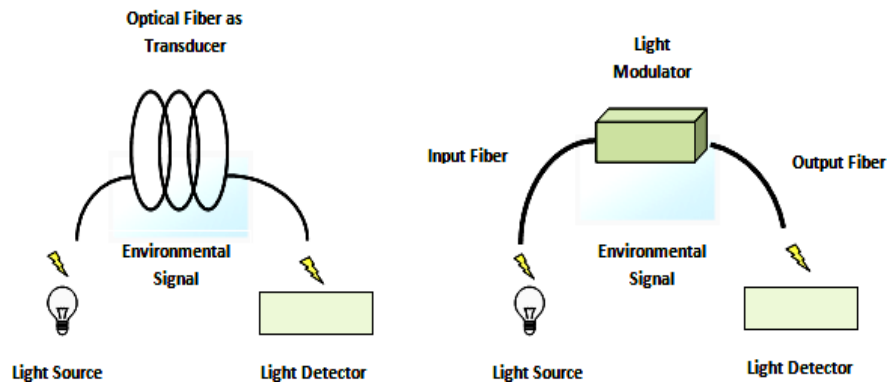


Figure 3. Types of FOSs. Intrinsic devices and Extrinsic devices.

Intrinsic FOSs directly employ an optical fiber as the sensitive material, sensor head, and also as the medium to transport the optical signal with information of the perturbation environment to be measured. They operate through the direct modulation of the light guided into the optical fiber. The light does not leave the fiber, except at the detection end, the output, of the sensor. These sensors can use interferometric configurations, Fiber Bragg Grating (FBG), Long Period Fiber Grating (LPFG), or special fibers (doped fibers) designed to be sensitive to specific perturbations. Light intensity is the simplest parameter to manipulate in intrinsic sensors because only a simple source and detector are required.

Extrinsic fiber optic sensor (EFOS): the optical fiber is simply used to guide the light to and from a location at which an optical sensor head is located. The sensor head is external to the optical fiber and is usually based on miniature optical components, which are designed to modulate the properties of light in response to changes in the environment with respect to physical perturbations of interest figure 3 (Extrinsic). Thus, in this configuration, one fiber transmits optical energy to the sensor head. Then this light is appropriately modulated and is coupled back via a second fiber, which guides it to the optical detector. Extrinsic fiber optic

sensors use a fiber optic cable, normally a multimode one, to transmit modulated light from a conventional sensor. A major feature of extrinsic sensors, which makes them so useful in such a large number of applications, is their ability to reach places which are otherwise inaccessible. For example, the insertion of fiber optic cables into the jet engines of aircraft to measure temperature by transmitting radiation into a radiation pyrometer located remotely from the engine. Fiber optic cable can be used in the same way to measure the internal temperature of electrical transformers, where the extreme electromagnetic fields present make other measurement techniques impossible. Extrinsic fiber optic sensors provide excellent protection of measurement signals against noise corruption.

Optical Sensor Types. Fiber optical sensors are sensors that can work in harsh environments where conventional electronic and electrical sensors have difficulties. They can sense various physical properties, such as pressure, position, strain, chemical changes, magnetic and electric fields, flow, vibration, light level, radiation and colour [3][6][9].

- Chemical sensors; remote spectroscopy, groundwater and soil contamination.

- Temperature sensors; largest commercially available sensors, range -40 °C to 1000 °C.



- Strain sensors; fiber Bragg gratings (FBG) technology, senses as little as 9 micro strain.

- Biomedical sensors; spectroscopic biomedical sensors, CO₂, O₂ and PH can be measured simultaneously, flow monitoring by laser dopplerimetry

- Electrical and magnetic sensors; appealing inherent dielectric nature, less sensitive to electromagnetic interference, small size and safer, they are almost always hybrid.

- Rotation sensor; based on the sagnac effect, two types ring laser gyroscope (RLG) and fiber optic gyroscope (FOG).

- Pressure sensors; based on piezoresistive technique or movable diaphragm, high performance (polarization based sensors); operating pressure ranges from 0-70,000 torr.

- Displacement and position sensors; one of the first optoelectronic sensors to be developed, simple sensors rely on the change in retro reflectance due to a proximal mirror surface, also referred as liquid level sensors.

Typical Fiber-Optical Sensors (FOSs) (Crack Sensors). FOSs are extensively used in various fields [14]. The FOSs used for crack detection mainly including grating sensors and distributed fiber-optic sensors. Crack detection FOSs are mainly used for the stability of reinforced concrete structures. They have a wide range of applications in the health and stability of bridges, buildings, tunnels, and highways.

In crack detection, an important challenge is that it is difficult to monitor the number and depth of cracks in concrete structures due to the uneven and complex materials. A distributed crack fiber sensor based on optical time-domain reflection, which does not need to pre-determine the position of the crack, and realizes the coverage monitoring of all cracks. The short light pulse is used as the light source, and the backscattered light power is

measured by OTDR. The formation of the crack is related to the bending angle of the optical fiber, and the bending leads to the loss of optical power. The relationship curve between backscattered power and light propagation distance decreases sharply at the crack. From this, the crack opening can be determined. One of the advantages of distributed optical fiber sensing is that it can monitor every point distributed along the optical fiber [13], thus it can accurately correspond to the location of the crack. Subsequently, on the basis of locating the crack position, Neha Niharika proposed a novel "S"-type optical fiber layout to increase the sensitivity while maintaining the distributed characteristics of the sensing system. Moreover, with the "S"-type fiber layout suggested by the solution, the sensitivity of crack openings is increased by 1.43 dBm/mm. In 2015, Gerardo Rodríguez demonstrated a method based on the optical backscattering reflectometer (OBR) to measure the generation, location, and width of cracks in concrete structures. A lot of uncertain structural damages are shown through cracks, thus the crack location and width are vital parameters. This OBR system can obtain continuous strain with higher spatial resolution and precision, and the experimental data calibrate the nonlinear model of the concrete slab, which can predict the crack location and width of different parts of the specimen. In 2018, Linked In and Yaming Li designed a new type of line crack sensor based on linear macroscopic bending loss of optical fiber. The sensor system overcomes the nonlinear relationship between macroscopic bending loss and crack opening displacement (COD), and verifies the simple linear relationship between macroscopic bending loss and COD of the optical fiber by using crack transfer device with gears.



Temperature Sensors. In the past few decades, with the rapid construction of buildings, bridges, and dams, researchers have focused on the health monitoring of concrete structures. The temperature effect of the concrete structure is closely related to its structural health [12]. Temperature monitoring determines the quality, thermal resistance, and cold resistance of the concrete structure. At present, the more matured technology is the distributed optical fiber temperature sensing. Different from local optical fiber sensing, distributed sensing can realize the test of thousands of data points by a single sensor.

In the earlier period, Y. J. Rao proposed an optical fiber Fabry-Perot sensor based on wavelength multiplexing, which can be used to simultaneously measure the static strain, temperature, and vibration of SHM. It can be surface mounted or embedded to realize distributed temperature sensing. Different from most studies focusing on the influence of the surrounding environment on the temperature change of concrete structures, Xiaotian Zou designed a Fabry-Perot

optical fiber temperature sensor to study the temperature change in the hydration process of concrete, and derived the temperature curve (as shown in Figure 4), which is used to calculate the apparent activation energy (E_a) and hydration heat ($H(t)$) of concrete, which can help us better understand the hydration of cement. When cement is mixed with water, an exothermic chemical reaction occurs to generate hydration heat. The data obtained through experiments show that when the water-to-cement (w/c) ratio is 0.4, 0.5, and 0.6 respectively, the peak temperature of the concrete specimen is 51.42 °C, 52.88 °C, 55.08 °C. The early temperature changes caused by hydration heat at different water-cement ratios are related to the temperature stress and cracks of the concrete structure. Therefore, during the hydration process, the temperature trend of the cement and the maximum temperature is crucial. These parameters can be used to predict future structural health.

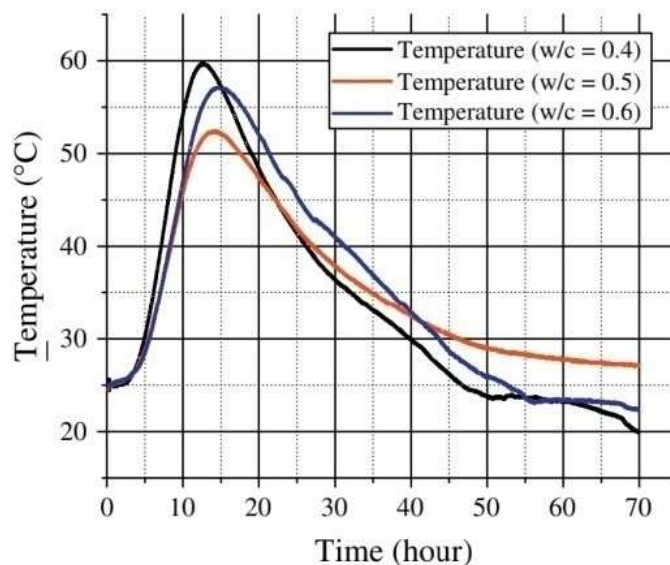


Figure 4. Concrete hydration experiment with water versus cement ratio 0.4, 0.5, and 0.6 using the thermocouple.



In addition, distributed temperature sensing (DTS) plays an important role in controlling and monitoring the cracks in concrete structures. In large concrete structures (such as large bases, bridges, dams, etc.), the hydration process heats the concrete structure after pouring large pieces of concrete. The outer surface of the concrete cools down faster than the inner surface. Because of the poor thermal conductivity of the concrete, a large temperature gradient is generated on the surface and inside. The uneven expansion of concrete caused by early temperature differences can cause thermal tensile stress on the surface. In the later period, it is constrained and deformed by the adjacent concrete or rock mass, which produces a tensile force on the constrained surface. When the tensile force exceeds the tensile strength, thermal cracking occurs [14]. Ouyang used the DTS system to provide crack control ideas for mass concrete structures in reservoir projects. This Raman-based DTS system usually consists of a DTS unit with an integrated OBR interrogation unit and multiplexer, computer, power supply, and optical

cable. They are covered by a graded-index multimode optical fiber with a refractive index of 50 μm and a coating layer with a diameter of 125 μm , and the outer layer is covered with low-density polyethylene. Each fiber optic cable is connected to the DTS unit through a pigtail (Figure 5). The pigtail is a short length of optical fiber with a dedicated connector at one end to protect the fiber core wire and paired with the channel of the multiplexer; the other end uses a fiber fusion splicer to fuse it with the optical cable. Through the inverse analysis method based on temperature simulation, the temperature measurement value in the concrete block is used as the basic data to determine the thermal performance of the cast-in-place concrete. Based on thermal stress simulation using thermal characteristics, the cracking risk of each concrete block is predicted and evaluated in a temperature control mode related to time-varying construction and environmental condition, greatly improving the efficiency of temperature adjustment and crack control in the construction of mass concrete.

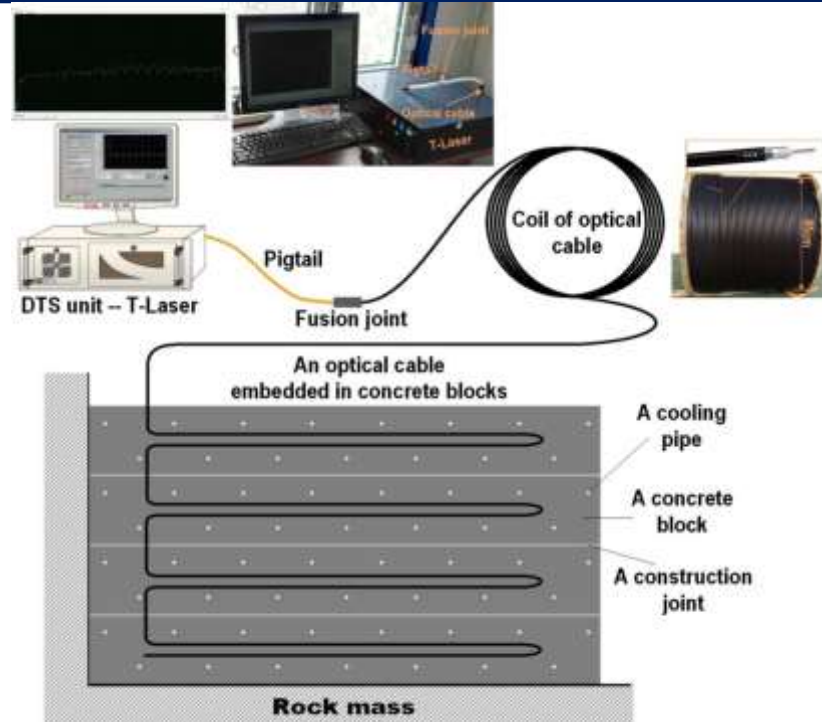


Figure 5. The diagram of the distributed temperature sensing (DTS) system.

Although distributed temperature sensing technology has matured, the point sensors are more suitable for monitoring the temperature of a limited measurement point. The point FOS technology can be developed owing to the unique advantages provided by the use of

optical fiber connecting the measuring location to the interrogating unit [11]. Moreover, low cost and mature packaging technology are also the advantages of point FOS widely used in temperature measurement in the industry.

References:

1. Kashyap, R., "Photosensitive Optical Fibers: Devices and Applications", Op. Fiber Tech., Vol.1, 1994.
2. R. Narayanaswamy, O. S. Wolfbeis, Optical Sensors: Industrial, Environmental and Diagnostic Applications, 2004.
3. P. Ficocelli, "Fiber optic Thermal Monitoring Systems for SAGD", PTAC Technology Information Session, March, 2008
4. Keiser, G. (1991). Optical Fiber Communications. (2ed), McGraw-Hill, ISBN 0070336172, NewYork USA.
5. Ghatak, A. & Thyagarajan, K. (2000). "An Introduction to Fiber Optics", Cambridge University Press, ISBN 0521571200, New York USA.
6. Yu, F. T. S. Yin, S. Ruffin, P. B. (2008). "Fiber Optic Sensors," CRC Press Taylor&Francis Group, ISBN 9781420053654, United State of America.
7. Zuhridinov H.Q. ELIMINATION OF VARIOUS HAZARDS THROUGH THE USE OF OPTICAL SENSORS IN THE ENERGY, CIVILIAN AND TRANSPORT SECTORS. 433-441 p.2022. <https://doi.org/10.5281/zenodo.7057515>



8. Zuhridinov Hayotbek Qaxramonjon o'g'li, "OPTIK TOLALI DATCHIKLARNING BOSHQADATCHIKLARDAN FOYDALANISHDAGI AFZALLIKLARI" «ОБРАЗОВАНИЕ И НАУКА В XXI ВЕКЕ». Выпуск №25 (том 4) (апрель,2022). Дата выхода в свет: 30.04.2022.<http://mpcareer.ru.445-449bet>.
9. Mirsagdiyev Orifjon Alimovich, Zuhridinov Hayotbek Qaxramonjon o'g'li, "QISHLOQ XO'JALIGIDA NAMLIK DATCHIKLARIDAN OQILONA FOYDALANISH USULLARI" Journal of Advanced Research and Stability ISSN: 2181 -2608. www.sciencebox.uz/482-484bet.2022y.
10. Zuhridinov Hayotbek Qaxramonjon o'g'li, "ANALYSIS OF SAFETY IN CONSTRUCTION SITES USING OPTICAL SENSORS" WEB OF SIENTIST: INTERNATIONAL SCIENTIFIC RESEARCH JOURNAL. ISSN: 2776-0979, <https://wos.academiascience.org/index.php/wos/article/view/1850>. 131-140 bet.
11. Zuhridinov Hayotbek Qaxramonjon o'g'li, "MA'LUMOTLARNI OPTIK DATCHIKLAR YORDAMIDA YETKAZISH VA O'LCHASH TIZIMLARINI ISHLAB CHIQUISH" Iqtisodiyotni raqamlashtirish sharoitida korporativ boshqaruv modellarining transformatsiyasi xalqaro ilmiy-amaliy anjumani. 10.24412/cl-36899-2022-1-237-241.
12. Zuhridinov Hayotbek Qaxramonjon o'g'li, "HOZIRGI ZAMONAVIY RIVOJLANAGAN DAVRDA OPTIK DATCHIKLARDAN FOYDALANIB TURLI SOHALARDAGI HAVFLARNI OLDINI OLISHNI O'RGANISH" Iqtisodiyotni raqamlashtirish sharoitida korporativ boshqaruv modellarining transformatsiyasi xalqaro ilmiy-amaliy anjumani. 10.24412/cl-36899-2022-1-231-236.
13. Abdazimov S.X, Zuhridinov.H.Q. ANALYZING THE RESULTS OF MONITORING THE SITUATIONS THAT MAY OCCUR IN EMERGENCY SITUATIONS OF BRIDGES THROUGH VARIOUS OPTICAL SENSORS. 80-88 p. 2022. www.scienticreview.com. ISSN (E): 2795-4951
14. Abdazimov S.X, Zuhridinov.H.Q. Prediction of Situations That May Occur in Emergency Situations of Bridges by Means of Optical Sensors. 55-59p.2022. Texas Journal of Engineering and Technology <https://zieniournals.com>. ISSN NO: 2770-4491