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Implementation of Optical and Electro-Optical Sensors In Robotics and Other Industries

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Abstract - The research on engineering experiment is a key step in translating technical development to industrial application. Active, optical range imaging sensors collect three-dimensional coordinate data from object surfaces and can be useful in a wide variety of automation applications, including shape acquisition, bin picking, assembly, inspection, gaging, robot navigation, medical diagnosis, and cartography[1]. An optical sensor converts light rays into electronic signals. It measures the physical quantity of light and then translates it into a form that is readable by an instrument. An optical sensor is generally part of a larger system that integrates a source of light, a measuring device and the optical sensor. This is often connected to an electrical trigger. The trigger reacts to a change in the signal within the light sensor. Electro-optical sensors are used whenever light needs to be converted to energy. Because of this, electro-optical sensors can be seen almost anywhere. Common applications are smartphones where sensors are used to adjust screen brightness, and smartwatches in which sensors are used to measure the wearers heartbeat, optical flow sensors, marine, medical, surveillance, surgical, civil applications and optical fibre gas sensors.

1 INTRODUCTION

OPTICAL and electro-optical sensors have attracted the lot of attention now days due to their applications and suitability in different fields like industry, space, manufacturing, chemical, marine and especially in the medical science[2][3]. Over the past two decades, electro-optic (EO) sensing technologies have been continually and viably developed as a practical and unique method for sensing electric fields in a minimally destructive way. This is because EO crystals are essentially transparent to both electromagnetic and optical waves. The unique, electrically-transparent aspect of these all-dielectric field probes enables exploration of the near-electric-field distributions of radio frequency (RF) radiators, such as antennas and arrays, or the internal-node diagnosis of high-speed electronic devices and circuits—without disruption to the signals present and without the complicated probe compensation necessary when employing conventional metallic probes. Regarding the electrical transparency of the sensor crystals, both the volume and permittivity (*i.e.*, capacitance) of the material, as well as its supporting embodiment are crucial factors. In this paper, different applications of sensors are reviewed.

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2 ABOUT FIBRE- OPTIC AND ELECTRO-OPTICAL (EO) SENSORS

A fiber-optic sensor detects changes in the light guided through an optical fiber when it is affected by external physical, chemical, biochemical, or any other parameters. It uses optical fiber either as the sensing element ("intrinsic sensors"), or as a means of relaying signals from a remote sensor to the electronics that process the signals ("extrinsic sensors"). Fibers have many uses in remote sensing. Depending on the application, fiber may be used because of its small size, or because no electrical power is needed at the remote location, or because many sensors can be multiplexed along the length of a fiber by using light wavelength shift for each sensor, or by sensing the time delay as light passes along the fiber through each sensor. Time delay can be determined using a device such as an optical time-domain reflectometer and wavelength shift can be calculated using an instrument implementing optical frequency domain reflectometry.

Electro-optical sensors are electronic detectors that convert light, or a change in light, into an electronic signal. They are used in many industrial and consumer applications, for example:

- Lamps that turn on automatically in response to darkness.
- Position sensors that activate when an object interrupts a light beam.
- Flash detection, to synchronize one photographic flash to another.
- Photoelectric sensors that detect the distance, absence, or presence of an object.

Optical Fiber Sensors offer significant advantages over other sensing methodologies. The advantages of Optical Fiber Sensors include [6]:

- Greater sensitivity;
- Reduced size;
- Reduced weight;
- Immunity to electromagnetic interference (EMI), since the fiber is not electrically conductive;
- Reduced cost;
- Versatility;
- Reliability;
- Compatibility to optical communication and telemetry.
- Large bandwidth.
- Operation at very high temperature ,pressure ,or voltage.
- Multiplexed or distributed measurement.
- Long range operation.
- Greater flexibility , allowing access to restricted areas.
- Resistant to chemically aggressive and ionizing environments.

Optical sensor measurands-

TEMPERATURE	CHEMICAL SPECIES
PRESSURE	FORCE
FLOW	RADIATION
LIQUID LEVEL	pH
DISPLACEMENT	HUMIDITY
ROTATION	VELOCITY
MAGNETIC FIELDS	ELECTRIC FIELDS
ACCELERATION	ACOUSTIC FIELDS

2 APPLICATIONS OF OPTICAL FIBER SENSORS AND ELECTRO-OPTICAL SENSORS

2.1 Minimally Invasive Robotic Surgery-

In minimally invasive surgery, surgeons use a variety of techniques to operate with less injury to the body than with open surgery. In general, it is safer than open surgery and allows you to recover faster and heal with less pain and scarring. Minimally invasive surgery is usually done on an outpatient basis or requires only a short hospital stay. During minimally invasive surgery (MIS), the surgical instruments are introduced into the body through small incisions. The major advantages are the reduced trauma and shorter recovery time for the patient. On the other hand, the surgeon looses tactile feedback, direct hand–eye coordination, and also two degrees of freedom of the instrument. As the instrument can only rotate and slide through the trocar point (the point where the instrument enters the body), the number of degrees of freedom is limited to 4. The accuracy of medical interventions can considerably be enhanced with the introduction of robots in minimally invasive surgery of soft tissues. The instruments are mounted on robot manipulators controlled by the surgeon through 'joysticks' (masters). This way, the surgeon can perform the operation in a more ergonomic way and his hand movements can be scaled and filtered to remove trembling and to enhance accuracy. Examples of commercial robots for MIS are the ZEUS® system from Computer Motion and the da Vinci® system from Intuitive Surgical.

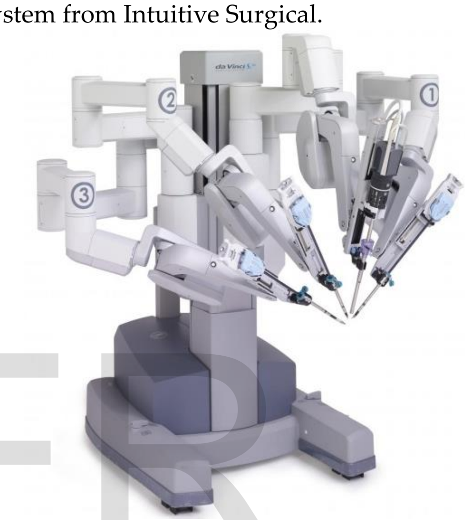

Fig 1. The da Vinci system from Intuitive Surgical.

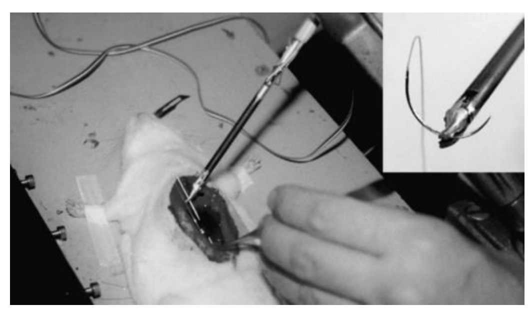

Fig 2. In vivo suturing tests on an anaesthetized rat using the instrumented needle driver. The insert shows how the needle is oriented in the jaws.

2.1.1 Sensor design:

A design based on optical fibres was chosen for reasons of safety as no leakage currents or interference signals can originate from it. Fig. 3 shows the basic layout of the sensor. It consists of two parts connected by a flexible connection. The upper part is connected to the tool while the lower part is connected to the instrument shaft. Three optical fibres, arranged at 120◦ intervals in the lower part, measure the relative displacement between upper and lower part through

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the intensity of the reflected signal. The fibres are placed axially because bending them inside the sensor over 90◦ would violate the minimum bending radius. Fig. 4 shows two possible configurations for each of the three sensing fibres. The first configuration is the simplest as it uses separate emitter and receiver fibres. In the second configuration, the light is reflected back into the same fibre. An optocoupler has to be used to couple the emitter (LED) and receiver (photodiode) to the same measurement fibre.

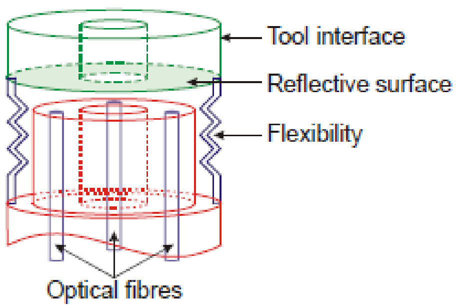

Fig 3. Working principle of the sensor: three optical fibers measure the deformation of the flexible structure through the intensity of the reflected light.[3]

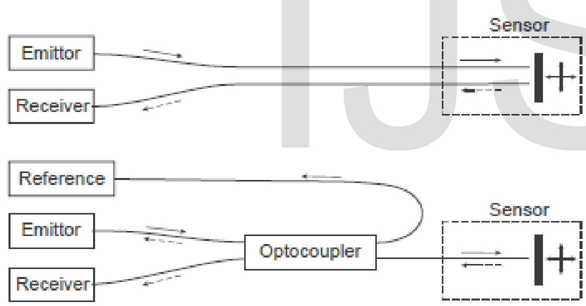

Fig 4. Two configurations for reflective position measurement with optical fibres.

The sensing fibre can measure the perpendicular distance from the surface or the lateral distance from an edge of this surface, depending on the sensor design. The emittor is fed with a 5 kHz sinusoidal signal with 0.85V amplitude and 3.35V offset, such that the LED remains in its linear domain. The receiver signal is filtered and amplified by two bandpass filters of 5 kHz in series. This amplitude modulation scheme removes drift and noise of sensor and amplifier.

2.2 Retinal Microsurgery-

Many clinical procedures involve intervention and manipulation of extremely small, delicate tissue structures. Retinal microsurgery is an example of the requirement for micron level maneuvers[9]. Retinal microsurgery requires extremely delicate manipulation of retinal tissue where tool-to-tissue interaction forces are usually below the threshold of human perception. Creating a force sensing surgical instrument that measures the forces directly at the tool tip poses great challenges due to the interactions between the tool shaft and the sclerotomy opening. The manipulation of vitreo-retinal structures inside the eye poses enormous challenges, due to tissue delicacy, surgical inaccessibility, suboptimal visualization, and the potential for irreversible tissue damage resulting from unintentional movement. In current practice, retinal surgery is performed under a surgical microscope. Small (20–25 gauge) surgical instruments are inserted through the sclera of the eye through operative sclerotomy sites (typically, 2–3).

Early work by Gupta et al. included use of a 1 DOF pick-like probe to measure forces in retinal surgery and to explore the feasibility of a simple auditory "sensory substitution" scheme to assist the surgeon in controlling these forces. Subsequently, Berkelman et al. developed a 3 DOF force sensor for use in ENT and eye applications with the JHU "Steady Hand" microsurgery system. Experience with this instrument shows that in vivo measurements are indeed feasible, but that discrimination between forces applied at the tool tip and forces from contact with the sclera may be a challenge if the force sensing is done distal to the sclerotomy point. The difficulty is not so much friction between the tool shaft and sclerotomy opening as it is lateral forces exerted on the tool shaft during tool manipulation. The conceptual design of the force-sensing tool is shown in Fig.5.

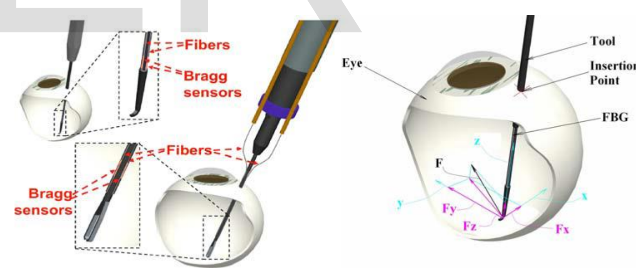

Fig5. (Left) Conceptual design of optical fiber force-sensing tool; (right) force coordinate system at the tip of the tool.

To mimic 25 gauge ophthalmic instruments, a 50-mm long titanium wire with 0.5 mm diameter was prepared as the tool shaft. Titanium was selected to provide the tool the necessary toughness and flexibility to allow maximal strain and resulting increased sensitivity. To integrate the FBG optical fiber into the shaft, a square section channel (160 × 160 μm) was machined into the surface along shaft's axial direction. The FBG sensor used is OS110, from Micron Optics, Inc. (Atlanta, GA), with a central wavelength of 1550 nm. The active fiber section of the sensor is about 10-mm long, starting 5mm from the tip of the fiber pigtail. An optical sensing interrogator, sm130–700 from Micron Optics Inc. (Atlanta GA), was used to monitor the sensor. The fibers themselves have very small diameters (160 μm in our current application), are immune to electrical noise,

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can be sterilized in various ways, and have excellent biocompatibility characteristics.

2.3 Electro-optical Proximity Sensor for Robotics-

A new amplitude-modulation-based proximity sensor that combines several novel features has been studied. The primary objective of the development was to obtain a robust proximity sensor for utilization in robotic active-sensing tasks. The new AM proximity transducer uses redundant measurements to improve the robustness of the sensor. The transducer design was optimized to provide increased robustness and increased measurement accuracy as the gripper nears the contact point[2]. A novel electronic interface circuit was designed to provide the required extended dynamic measurement range for the utilization of the proximity sensor in an active-sensing environment. The circuit's protective mechanisms against light noise allows operation of the sensor in typical manufacturing environments. The features of the AM transducer allow the utilization of a new CPG of surfaces methodology. This methodology was employed in an attempt to address the problem of robustness of AM proximity sensors to surface-reflection characteristics. The sensor was calibrated individually for eight different materials using CPS, as well as globally for all eight materials and for two groups of materials (metals and dielectrics) using CPG. The potential application of the proposed proximity sensor in controlling the micro-movements of a robot's gripper was explored by a prototype active-sensing algorithm. The combination of active sensing and the proposed multi-region calibration improves the grasping accuracy by more than an order of magnitude in comparison with a single-measurement scheme. Physical experiments verified the expected good performance of the CPG-calibrated proximity sensor for all the *a priori* considered surfaces, as well as for surfaces not considered before.

2.4 Minimally Destructive Microwave Field Probing-

The recent design methodologies for fully dielectric electro-optic sensors, have applications in non-destructive evaluation (NDE) of devices and materials that radiate, guide, or otherwise may be impacted by microwave fields. In many practical NDE situations, fiber-coupled-sensor configurations are preferred due to their advantages over free-space bulk sensors in terms of optical alignment, spatial resolution, and especially, a low degree of field invasiveness. It is apparent that the design and implementation of EO sensors are crucial to achieving non-destructive microwave sensing applications with suitable sensitivity. One of the most widely used configurations is the mounting of a tiny EO-sensitive crystal tip onto a fiber facet, as this allows the development of all-dielectric embodiments with reasonably small size that minimize distortion of the electric fields to be sensed.

2.4.1 Design Methods of Fiber-Coupled EO Probes:

The refractive indices of the EO sensor materials are linearly affected by electric fields that pass through the sensor media. As the properties of the EO-sensor medium along the optical path are modified during exposure to low-frequency electric fields (relative to the optical frequency of the light beam), the light becomes phase-modulated by an additional, field-induced optical phase delay experienced by the part of the light polarized along specific axes of the crystal. The modulated portions of this sensing light beam are eventually demodulated using a photodiode that receives either transmitted or reflected light from the sensor. In practical respects, the reflective scheme is generally preferred, with a sensor tip as the terminal of the optical sensor and the light being modulated at the sensor terminal when it is exposed to an electric field[5]. The reflected beams to be detected are efficiently returned from the sensor using a number of common methods: a mirror; total internal reflection; highly reflective surfaces from the device under tests; or through fabrication of a resonator on the sensor plate. The most distinguishing feature of EO sensors for use in electromagnetic-field detection is their distinctly low-invasiveness compared to common electrical-field probes.

Table 1. Comparison of the five probe types.

Probe type	Probe name	Sensitivity	Fabrication difficulty	Need for coating	Need for analyzer	Invasiveness	Temporal resolution
I	conventional	good	easy	once	yes	excellent	excellent
II	interference	fair	easy	no	no	excellent	excellent
III	thick-interference	excellent	easy	once	no	fair	good
IV	resonance	excellent	medium	twice	no	excellent	good
V	multi-layer	good	hard	no	no	good	good

Low invasiveness is one of the distinguishing features of EO sensors. The sensor volume that interacts with the *E*-fields to be measured is a key factor in the invasiveness.

2.5 Optical Proximity Sensors: Reactive Grasping-

For robots to reliably grasp novel objects, they must be able to sense the object geometry sufficiently accurately to choose a good grasp. Reactive grasping implements optical proximity sensors embedded in the fingers of the robot. Optical sensors are highly sensitive to surface reflection properties. Alternatively, capacitive-based proximity sensors have also been used. While invariant to surface properties, these capacitive-based sensors have difficulty detecting materials with low dielectric contrast, such as fabrics and thin plastics.
A basic optical sensor consists of an emitter, photoreceiver, and signal processing circuitry. The light from the emitter is reflected by nearby surfaces and received by the photo-

receiver. The amplitude and phase of the light vary as a function of the distance to the surface, its orientation, and other properties of the surface material (reflectance, texture, etc.). In amplitude-modulated proximity sensor design, the most commonly preferred method, these variations in amplitude can be converted into pose estimates by measuring the response from constellations of at least three receivers focused at the same point on the target surface. Although conceptually simple, modelling the pose of unknown surfaces is difficult because of the non-monotonic behaviour of the proximity sensor receivers.

Fig6: Three-fingered Barrett Hand with our optical proximity sensors mounted on the finger tips[5].

2.6 Micro-Robotics: Optical Three-axis Tactile Sensor for Micro-Robots[7] -

Microbotics (or microrobotics) is the field of miniature robotics, in particular mobile robots with characteristic dimensions less than 1 mm. The term can also be used for robots capable of handling micrometer size components. The optical tactile sensor, comprises an optical waveguide plate, which is made of transparent acrylic and is illuminated along its edge by a light source. The light directed into the plate remains within it due to the total internal reflection generated, since the plate is surrounded by air having a lower refractive index than the plate. A rubber sheet featuring an array of conical feelers is placed on the plate to keep the array surface in contact with the plate. If an object contacts the back of the rubber sheet, resulting in contact pressure, the feelers collapse, and at the points where these feelers collapse, light is diffusely reflected out of the reverse surface of the plate because the rubber has a higher refractive index than the plate. The distribution of contact pressure is calculated from the bright areas viewed from the reverse surface of the plate. The sensitivity of the optical tactile sensor can be adjusted by texture-morphology and hardness of the sheet. The texture can be easily made fine with a mold suited for micromachining because the texture is controlled by adjusting the process of pouring the rubber into the mold. This process enables the production of a micro-tactile sensor with high density and sensitivity by using the above mentioned principle of the optical tactile sensor.

2.7 Optical Flow-

Optical flow or optic flow is the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer (an eye or a camera) and the scene. An optical flow sensor is a vision sensor capable of measuring optical flow or visual motion and outputting a measurement based on optical flow. Various configurations of optical flow sensors exist. One configuration is an image sensor chip connected to a processor programmed to run an optical flow algorithm. Another configuration uses a vision chip, which is an integrated circuit having both the image sensor and the processor on the same die, allowing for a compact implementation.

Optical flow sensors are also being used in robotics applications, primarily where there is a need to measure visual motion or relative motion between the robot and other objects in the vicinity of the robot.

In the mobile robotics field, infrared sensors are being widely used for many applications, such as navigation and localization. The most widely used field in navigation uses the optical flow or image subtraction in human detection from infrared camera on mobile robot[8].

Fig.7 : The mSecuritTM mobile surveillance robot.

eg.the real-time human detection through processing video captured by a thermal infrared camera mounted on the Spanish private company MoviRobotics S.L. indoor autonomous mobile platform mSecurit™. The mSecurit™ mobile platform has been specially designed for surveillance tasks. The robot is able to detect humans with feeded algorithms with thermal infrared frames. There is an intelligent switching between image subtraction and optical flow, depending on the platform movement and the processing load. Surveillance can be active on the whole route or only in certain known points.

2.8 Structure Health Monitoring-

From many points of view, fiber optic sensors are the ideal transducers for civil structural monitoring.

Being durable, stable and insensitive to external perturbations, they are particularly interesting for the long-term health assessment of civil structures. Many different fiber optic sensor technologies exist and offer a wide range of performances and suitability for different applications.

Structural health monitoring is certainly one of the most powerful management tools and is therefore gaining in importance in the civil engineering community.

A typical health monitoring system is composed of a network of sensors that measure the parameters relevant to the state of the structure and its environment[17]. For civil structures such as bridges,
tunnels, dams, geostructures, power plants, high-rise buildings and historical monuments, the most relevant parameters are:

• Physical quantities: position, deformations, inclinations, strains, forces, pressures, accelerations, and vibrations.
• Temperatures.
• Chemical quantities: humidity, pH, and chlorine concentration.
• Environmental parameters: air temperature, wind speed and direction, irradiation, precipitation, snow accumulation, water levels and flow, pollutant concentration.

The first successful industrial applications of fiber optic sensors to civil structural monitoring demonstrate that this technology is now sufficiently mature for a routine use and that it can compete as a peer with conventional instrumentation.

An example citing the civil aspect of optical fiber sensor, Bridge strengthening and maintenance is the most important work of bridge safety. The bridge general status and the reinforcement effect can't be monitored effectively using conventional strengthening and maintenance methods. It is a necessary and urgent task to develop a new type of sensor monitoring system, for the real time and long term monitoring of loading state and reinforcing effect of the old bridges. We have constructed a real-time, multi-parameters and long-distance reinforcement monitoring system by combining the optical fiber sensing technology which has particular advantages with the mature conventional reinforcement methods.

2.9 Optical-Fibre-Based Gas Sensor Systems-

The spectroscopic sensing of chemical species is not a new technique. Most analytical chemistry laboratories possess several spectrophotometers. These are used for the recognition of a wide range of chemical species from their characteristic absorption, fluorescence or Raman-scattering spectra. Optical gas sensing methods are essentially similar, but usually are more dedicated versions of such spectrometers.

3 CONCLUSION

The optical and electro-optical sensors, though relatively newer in the field of sensing, are gaining much popularity. Advantages over conventional sensors in the field of sensing has given the sensors a vast field of experimentation, implementation and improvement. In this paper, several industrial applications of optical and EO sensors have been discussed. Clearly, optical sensors and related technologies are being used in variety of applications. Due to small size, precision, accuracy, durability, ease of approach, and fast feedback, make optical and EO sensors important part of surgical, medical, civil, chemical, military, and many more fields. It is difficult to find a common reason for the success of so diverse types of sensors, each one seems to have found a niche where it can offer performance that surpass or complement the ones of the more traditional sensors. If three characteristics of fiber optic sensors should be highlighted as the probable reason of their present and future success, it would be the stability of the measurements, the potential long-term reliability of the fibers and the possibility of performing distributed and remote measurements. Furthermore, with the invent of micro and nano level optical and electro-optical sensors, and the much larger market of fiber optic telecommunication, offers an interesting potential for cost reduction in most components used for sensing applications. In the near future it is therefore to expect that fiber optic sensors and electro-optical sensors will consolidate their presence in the structural sensing industry.

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