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DEVELOPMENT OF A ROBUST ELECTRO-OPTICAL PROXIMITY SENSOR

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Abstract **- The development of a robust fiber-optic proximity sensor is presented. A method is proposed by which to solve the problem of robustness of amplitude- and phase-modulated electro-optical proximity sensors to variations in surface-reflection characteristics, and to reduce the influence of distance and orientation measurements on one other. The method comprises three different methodologies, which are combined for better efficiency: integration of distance and orientation sensors, a novel polarization-based optical-filtering approach, and active sensing. Emphasis is given to unique solutions for background-noise interference and dynamic-range-limitation problems.**

I. INTRODUCTION ([1], [2])

The next generation of advanced robotic manipulators, working in more complex and constantly changing environments, must possess the capability of adapting to the imprecise features of their evolving surroundings. Employing various sensors in order to obtain information about the environment will facilitate this desired adaptivity. These sensors can be categorized into three groups according to their range of operation relative to the robot's gripper: medium-range sensors (vision, range-finding), short-range sensors (proximity), and contact sensors (tactile).

Proximity sensors, measuring the distance and orientation of an object relative to the gripper, are needed in order to bridge the uncertainty gap between the gross proximity-estimation of a vision system, and the direct contact required for tactile sensing. The range of the proximity sensor must be sufficiently large to compensate for possible errors of the vision system, while the accuracy must permit effective grasping of the object.

Many types of proximity sensors have been built; they employ various coupling media including sound, magnetic field, electric field and light. Presently, the electro-optical medium seems to be the most appropriate for the tasks described above. The primary reasons for this are: the relatively small size of an electro-optical sensor, its range of operation, and the fact that almost no restrictions are imposed on the object's material. Conventionally, electro-optical proximity sensors utilize one of two methods of operation: the triangulation principle, and the amplitude- or phase-modulation of light intensity. For various reasons (including the smaller size of the sensor head), amplitude- or phase-modulation schemes are more suited for mounting on a gripper, and are more commonly used.

II. BACKGROUND: LIGHT REFLECTION AND POLARIZATION

Two different approaches are usually followed in describing optics in general, and reflection in particular. These are the physical approach, based directly on wave theory and Maxwell's equations, and the geometrical approach which uses a simplifying approximation. Reflectance models using these approaches are described in [3] (physical) and [4] (geometrical). The latter uses a simpler mathematical formulation, but cannot be applied when the surface exhibits details whose dimensions are comparable to the optical wavelength, or smaller. A combined model is presented in [5].

Several mechanisms are involved in producing the reflectance pattern of a surface, resulting in three components: the specular spike, the specular lobe, and the diffused lobe (Fig. 1).

The specular spike is produced by very smooth (mirror-like) surfaces. In the manufacturing environment such spikes will exist in reflections from polished and coated surfaces. The specular lobe is produced by a (random) distribution of micro-planes whose dimensions are greater than the optical wavelength but much smaller than the beam width. This reflection is typical to roughly sanded objects. Both specular-reflection types affect the polarization of an initially-polarized light beam in the same way: the polarization azimuth will be shifted according to the reflection angle and the surface's parameters. Since the specular lobe is created as a result of reflection from a distribution of surfaces, the polarization shift is also distributed. This distribution, however, has a very small variance.

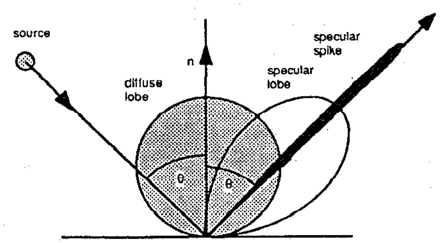

Fig. 1. Three types of reflection.

The diffused lobe originates from diffraction, either from very rough surfaces with a small correlation distance, or from internal refraction. Because of the high conductivity of metal surfaces, most of the light reflects off the interface between the metal and the air, while the portion that penetrates into the metal surface is absorbed. Accordingly, the reflection intensity originating from internal refraction in metal is practically zero. In dielectrics however, a large portion of the light penetrates into the surface, and then reflects back out as diffused light. It is important to emphasize that an initially polarized light beam will become randomly polarized through diffused reflection ([6]).

Mechanically machined objects, whose surfaces exhibit some periodic roughness, will have a series of specular spikes instead of only one. Reflection with several specular lobes is also possible. In the simple cases (such as for saw-tooth shaped grooves) the exact pattern of the scattering can be calculated based on the geometrical properties of the periodic grooves. However, a slight change in the periodic pattern of the grooves will result in a large change in the reflection pattern. Moreover, the periodic properties of machined objects are almost always asymmetrical and non-uniformly distributed over the surface. The non-uniformity causes the reflection pattern to vary rapidly as a function of the location on the surface, while the asymmetrical property causes rapid variations as a function of the angle of rotation around the surface normal.

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III. PHASE- AND AMPLITUDE-MODULATED PROXIMITY SENSORS

The common phase-modulated (PM) proximity sensor consists of at least two light sources and one photodetector (Fig. 2). The light sources are driven by modulated sinusoidal signals having a 90° phase difference. The phase and the amplitude of the detected signal are both functions of the sensor's geometrical parameters, the reflectivity characteristics of the object's surface, and its distance and orientation.

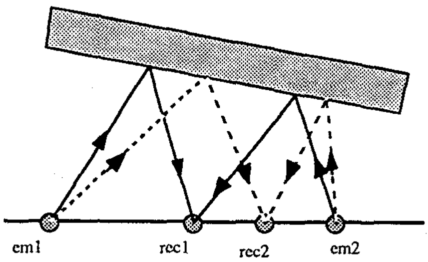

Fig. 2. A phase-modulated proximity sensor. Receiver 1 is suited to orientation measurement, and receiver 2 is suited to distance measurement.

Usually only the phase information is used, and the amplitude is completely neglected or used only for verifying the likelihood of error ([7], [8]):

$$V_{em1}(t) = a * \cos \omega t \tag{1}$$

$$V_{em2}(t) = b * \sin \omega t \tag{2}$$

$$V_{rec} = A * V_{em1} + B * V_{em2} \tag{3}$$

$$V_{rec}(t) = C * \sin(\omega t + \varphi) \tag{4}$$

Where:

a, b the intensities of the emitted signals.

A, B attenuation as a function of the geometrical parameters and the reflection characteristics.

C combined attenuation-function.

φ combined phase-shift.

V_{em1} emitter 1 control voltage.

V_{em2} emitter 2 control voltage.

V_{rec} receiver output voltage.

A basic amplitude-modulated (AM) sensor, on the other hand, usually consists of one light source and several photodetectors (Fig. 3). The signal amplitude at each detector is a function of all the parameters mentioned above. The distance and orientation can be extracted by comparing the values of the detector outputs. In any measurement, at least two detectors are used in order to compensate for changes in various parameters such as light-source intensity ([9], [10]). Typical output curves of an AM sensor are shown in Fig. 4.

Both the PM and the AM sensors possess a very useful feature: they can be arranged such that their accuracy will increase as the gripper nears the contact point, at which both the orientation and the distance are zero ([7], [9]). In the case of distance measurement, the sensitivity and accuracy of the sensor is closely related to one over distance squared. However, because of dynamic-range limitations, a trade off exists between the desired maximum accuracy near contact, and the maximum range of operation. These and other considerations must be taken into account when designing the geometric features of the sensors in either case, and in setting the ratio between the a and b parameters of the PM sensor, in particular.

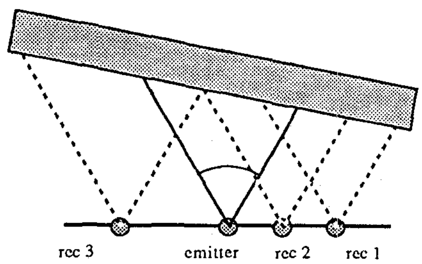

Fig. 3. An amplitude-modulated proximity sensor. Receiver pair 1 and 3 are suited to orientation measurement, and receiver pair 1 and 2 are suited to distance measurement.

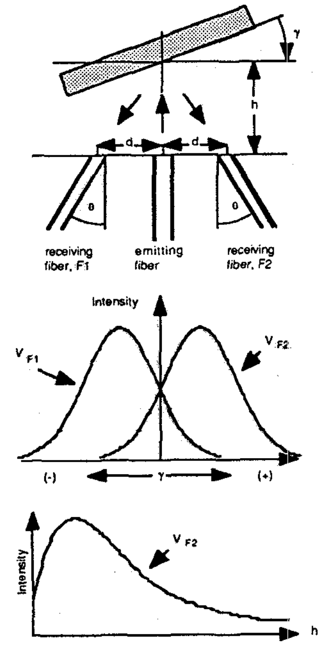

Fig. 4. Typical AM sensor curves: light intensity in a fiber-optic receiver as a function of the orientation (γ) and the distance (h).

IV. INTEGRATION OF ORIENTATION AND DISTANCE SENSORS

Our design of a proximity sensor capable of utilizing both the PM and AM schemes, carried out in the Computer Integrated Manufacturing Laboratory (CIMLab), was directed towards achieving a monotonic relationship between a controlling variable (distance, orientation) and a measured parameter (phase, amplitude). The associated curves should be influenced minimally by other variables. In general, orientation sensing requires symmetry, while distance sensing requires asymmetry. Since the complete isolation of either feature is not possible, a simple single-purpose sensor cannot supply accurate measurements without proper calibration and a prior knowledge of the other parameters. This means that in order to supply accurate measurements from a distance sensor, the surface orientation in both dimension must be known; the same situation applies to orientation sensing.

One possible way of solving this deadlock problem is through iteration, in which the initial set of measurements $\overline{y}$ is used to calculate the gross variable estimation, $\overline{x_0} = f(\overline{y},0)$, then, $\overline{x_1} = f(\overline{y},\overline{x_0})$, and so on. Here, each of the x_i is affected only by some of the measurements $\overline{y}$. The convergence of this solution approach has not been tested. Though possible, this method is more costly and complex than the direct calculation of, $\overline{x} = f(\overline{y})$, where every x_i is affected by all of the measurements $\overline{y}$.

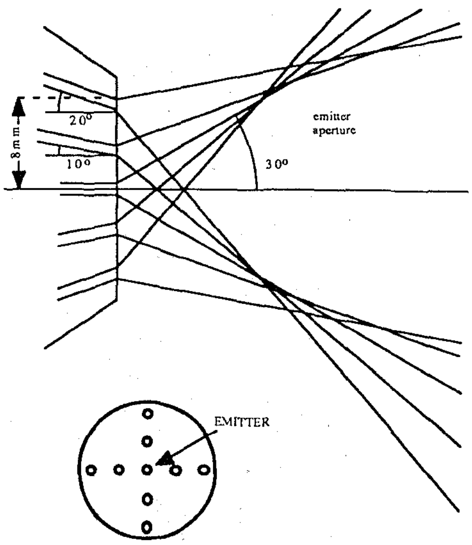

Fig. 5. Sensor-head design.

The design of the sensor head allows for its use in either AM- or PM-based sensor schemes. Currently the AM-scheme is under investigation using one emitter (Fig. 5). In this scheme, the new sensor supplies eight different measurements $\bar{y}$, which are initially transformed to a set of eight reasonably independent values $\bar{y}'$, each corresponding primarily to one parameter. This transformation is based on an analysis of the attenuation in the path to each detector. Further, various processes can be applied to mutually correct these values. These processes can be based on techniques such as sensor-fusion, neural-networks, or "simple" curve-fitting in eight-dimensional space.

The accumulation of the data points needed and attainment of the parameters for this process are done using an automatic testing procedure. The transformation of the initial measurements is done while collecting them and after a data-base is built. The transformed data are then processed off-line to extract the calibration parameters.

V. ROBUSTNESS TO SURFACE CHARACTERISTICS

The most serious problem related to either AM- or PM-based sensors is their susceptibility to variations in the reflectivity characteristics of measured objects. In general, objects made of different materials will reflect light in different ways. Furthermore, two objects made of the same material but with different surface roughnesses will not appear as equal to the sensor. This problem is rarely addressed in the literature, and when it is considered the proposed approaches are quite limited. They generally include optimization of the robustness of the sensor to surface characteristics by geometrical design of the sensor ([10]), or construction of a calibration-per-surface database, and thereby usage of apriori knowledge in order to pick appropriate calibration-information ([7], [9], [11]).

A truly adaptive and robust system, however, cannot rely on such solutions. Accuracy achieved via using optimization by geometrical design is far lower than the accuracy needed from such sensors. As for the other approach, building a large data-base of calibration information for each one of the possible surfaces is costly in initial setup time. Furthermore, the data-base must be updated with the results of a new calibration, every time a new object is added to the object-set handled by the robot. Apriori knowledge of the surface identity is also a severe restriction on the system. Also, this approach cannot be used when the objects to be handled by the robot are manufactured by a non-exact process.

Moreover, when the object's surface is machined using a grinding tool, or any other non-random process, the reflection of light from such a surface will have unique features. These features can be both asymmetrical and non-uniform. As a result, calibration for such a surface is not conventionally possible.

A unique and absolute solution to the problems described above has not yet been found, and perhaps does not exist. However, several approaches to improving upon the accuracy and robustness of such proximity sensors have been suggested by our work in the CIMLab. Correspondingly, the new design of a distance and two-degree-of-orientation sensor developed employs both these methodologies, combined suitably for greater sensor efficiency.

VI. BLOCKING SPECULAR REFLECTION

Using optical filtering based upon polarization cues, an attempt has been made here to solve the surface-robustness problem as near as possible to its source, even before the measurement is made. The surface-related problems arise primarily from the unique specular-reflection pattern possessed by any surface. It has been demonstrated that specular reflection can be blocked such that the measurements will use only the diffused reflections, which, except for intensity, are almost identical for any surface and material type.

Specular reflection can be blocked using polarizers as described in Fig. 6. An unpolarized light beam, originating from a light source, is polarized by a linear polarizer. This light is then reflected from the surface through both diffused and specular reflection. The specular component is still linearly polarized, while the diffused component is unpolarized. A second polarizer is mounted on the detector such that its transmission axis is perpendicular to the polarization direction of the specularly reflected light. The detector thus receives only that part of the diffused light whose polarization is passed by the second polarizer.

Several factors can adversely affect the efficiency of this proposed method. The main limitation lies in the reception of some of the specularly reflected light, which propagates as a result of two factors:

1) The efficiency of available polarizers is limited, and they might be difficult to mount in the exact position desired on a miniature sensor.

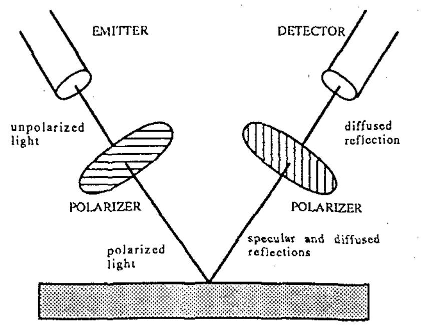

Fig. 6. The use of polarizers to block specular reflection.

2) The range of the possible orientations of the surface, and the range of angles between the light source, various reflecting micro-planes on the surface and the detector, cause a range of polarization azimuths instead of a single distinct one. The transmission axis of the second polarizer, therefore, can never be exactly perpendicular to the polarization of all specularly reflected light.

The adverse effect of these two factors is especially noticeable when the ratio between the specular and the diffused reflection-intensities is large, such as in the case of the extremely smooth surface of polished metal.

The degree of uniformity achieved by this method also depends on the deviation of the diffuse-lobe characteristics from an ideal cosine function (Fig. 7). The main problem that arises with this method is an increased demand on the sensor's dynamic range. There exists a wide range of possible attenuations along the optical path from the light source to the receivers. This problem is addressed later in this paper.

The use of the specular-reflection-blocking-by-polarization method is not limited to this application alone. Another application, together with a more thorough description of the method can be found in [12].

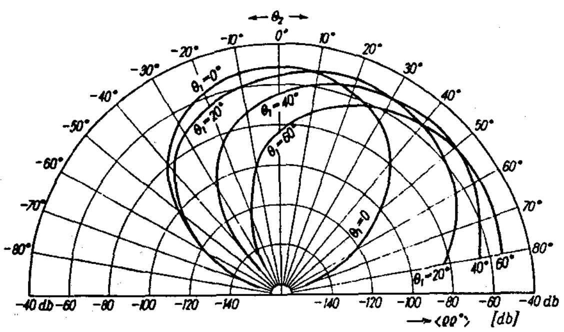

Fig. 7. The scattering diagram of a two-dimensional, very rough, normally-distributed surface. The diagram shows intensity as a function of the reflectance angle (θ_2), with the incident angle (θ_1) as a parameter.

VII. ACTIVE SENSING

Completely accurate and robust measurements might not be achievable even after applying the methods described above. Thus, in order to increase the effectiveness of the process of grasping an object, a complementary active-sensing technique has been added. The sensor is initially calibrated using measurements acquired on a wide selection of surfaces. For this calibration, various types of surface were prepared, using materials such as aluminum, copper, brass, stainless steel, Teflon, PVC, and wood. Each sample of these materials was prepared with two or more different surface roughnesses.

The calibration data-base consists of a vast number of measurements, taken at selected points in the three-dimensional variable space (distance, horizontal orientation and vertical orientation). The same points were used to obtain measurements from surfaces of every material and roughness. The space-variable points are not selected randomly, nor are they evenly spread. Rather, they are selected according to a special distribution function designed to achieve maximum accuracy in the region where each of the two orientations and the distance approach zero. This region represents the preferred trajectory of the robot's gripper when approaching the target surface, and the target itself. The measurements gathered are then used to create calibration parameters for the sensor. It is envisaged that several distinct calibration-parameters sets can be gathered, which match data points from material groups using similar surfaces. The various calibration parameters obtained can be used later by the active-sensing algorithm.

Active sensing is based on the usage of multiple measurements taken at different locations in order to better estimate the measured features. This method is widely used in various vision and range-finding systems ([13], [14], [15]), but it is not yet commonly employed by proximity sensor designers. At selected steps in the path, measurements can be taken, compared to the expected values, and stored in a history file. Using the results of these accumulated comparisons, the location for the next step and the expected values of the measurements there can be calculated.

During the first stage of the active-sensing process, the selection of locations at which measurements will be taken is directed towards collecting categorizing information. This information is used to determine the surface type and to select the most appropriate calibration-parameters set. In the second stage, the robot's gripper is aligned with the normal of the object's surface. This is done for two reasons: first, the distance measurements are more accurate when the orientation angle is zero (as measured from the surface normal); more importantly, this is necessary to avoid the chance of the gripper edge touching the object. In the final stage, the gap between the gripper and the object is carefully closed until contact is made, at which point the control is moved to the tactile sensor.

The result of this active-sensing approach is a self-calibration process that, potentially, can fine-tune the sensor to the surface characteristics during the gripper's approach to the object.

The available data-acquisition process is designed to supply measurements at a rate of up to 10kHz. This will enable measurements to be taken while the sensor is in motion. However, in order to utilize this real-time feature of the sensor, the active algorithm has to be correspondingly fast. Another requirement of this active-sensing concept is the possibility of direct control over the robot's gripper during the grasping process.

VIII. NOISE CONSIDERATIONS

Proximity sensors, mounted on a robot gripper, are meant to operate in a very noisy environment. In particular, those sensors based on light transduction are prone to intervention from many possible external sources of light. Sunlight and sources involving hot objects (e.g. tungsten lamps) emit light in both the visible and near infrared bands. Other high-temperature sources, that often exist in a manufacturing environment, also emit light in the infrared region. This light sets the "background noise" level in which the sensor operates. Other sources of light are even more disturbing: The light of fluorescent lamps is modulated at the electric power frequency (50/60 Hz) and its harmonics; Welders emit short bursts of light which are especially strong in the ultra-violet region. Because of all these disturbances, it is necessary to add to the light-transducer-based sensor some protective mechanisms.

The required immunity to external light disturbance is achieved here by a combination of two methods, namely, the use within the sensor of a narrow optical band and modulation of the light. The wavelength chosen for transducer operation is in the near-infrared region to avoid as much of the light noise as possible. The light source for the transducer is a laser diode, capable of emitting 20mW of light power at 810nm. The received light, in turn, is passed through a corresponding optical filter. The minimum width of the optical band of the filter is set by geometric features and the tolerances of the sensors. Most critically, the center frequency of a pass-band interference filter is a function of the angle between the light beam and the filter's normal. Therefore, in order to cover the aperture of the sensor, the bandwidth needed can be approximated as:

$$\Delta\lambda = 2\lambda_{max}\left(1 - \sqrt{1 - \left(\frac{n_o}{n_e}\right)^2 \sin\phi}\right) \qquad (5)$$

Where:

ϕ the sensor's aperture.

n_o refractive index of the external medium (air).

n_e effective refractive index of the internal medium.

λ_{max} the filter's center wavelength.

Additional tolerance is needed to cover other parameters such as laser-wavelength drift as a function of temperature and output power.

Additional noise immunity of both an optical and electrical kind is achieved by modulation. The laser diode is modulated by a 10kHz square wave, while the received signals are passed through a high-Q band-pass filter, and sampled at the output sine-wave peak (Fig. 8). This also helps to resolve the problem of biassing and its temperature-related drift in the sensor. As a result, in practice, the optical noise can be reduced to under the measurable level even in extremely bright, "light-infested" surroundings.

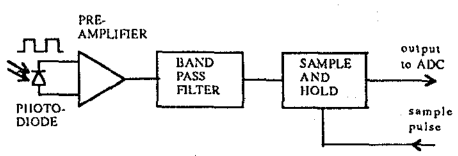

Fig. 8. The receiver circuit.

In order to reduce the effects of electrical noise in the sensory circuit as much as possible, the complete circuit, containing the laser driver and eight receivers, is built on a single shielded PC I/O card. The emitted laser light and received reflection-samples are conducted between the card and the sensor-head using fiber-optic cables having a 1mm core. This facilitates the operation of the sensitive low-noise circuitry appropriately remote from the high currents of the robot's motors.

IX. DYNAMIC RANGE

Dynamic range is a very important parameter of any sensor and particularly of position sensors. In practice, the light intensity at the receiving end of the sensor varies strongly as a function of many parameters. For example, light intensity relates to one over distance squared. Thus for even a modest operating range, this can result in a 100:1 range of light intensities at the receiver. It is important to emphasize at this point that the light-detection action in the receiver converts light power to current. Therefore the range of current intensities for various distances is also 100:1, which translates to a 40db of measurements range (rather than the 20db variation in distance itself). The other measured parameter, surface orientation, is subject to a similar 40db of measurements range. However, there exist other parameters, such as overall reflectivity of the surface and polarization attenuation, that for different surfaces can vary in even a more extreme manner. In fact, so extreme are the variations that one can easily come to the conclusion that no receiver circuit will be able to supply the dynamic range required.

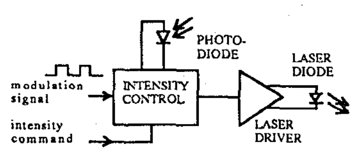

Fig. 9. The laser-driver control circuit.

The solution to this problem can be found at the transmitter end. In addition to the dynamic range of the receiver circuit, the light intensity at the source can be changed such that the output intensity remains adequate for measurement in a manner similar to the "floating point" scheme. The laser's output power is monitored with the help of a photo-diode integrated with it (Fig. 9). Using a closed-loop driver, the output intensity can be brought to the desired level in a fraction of a modulation-pulse duration. In this process of dynamic intensity control, a sample-and-hold circuit is employed in order to minimize transient effects in the feedback loop induced by the modulation process. This approach to extending the sensor's dynamic range is a key element in the implementation of the overall polarization scheme, and in the desired enlargement of the measurable distance and orientation ranges.

X. DISCUSSION

Two new methodologies, the elimination of specular reflection and active sensing, have been employed in an attempt to solve the problem of robustness of AM- and PM-based electro-optical proximity sensors to surface reflection characteristics. A proximity sensor that utilizes these methodologies has been developed, and is currently undergoing evaluation. In this process, thought was put, not just towards the development of these methods, but also towards the analysis of calibration schemes and the design of supporting electronic circuitry that allow operation of the sensor in a typical manufacturing environment. In addition, a unique approach was developed and employed to extensively increase the dynamic range of position measurements.

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