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OPTICAL PROXIMITY SENSOR SYSTEMS FOR INTELLIGENT ROBOT HANDS

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Abstract. Optical proximity sensors are low-level vision sensors delivering low- and mid-range multidimensional information about the robots end-effector environment. Due to the fast signal processing they can be easily integrated in real-time robot control tasks. The paper presents the basic mechanical, hardware and software design principles of such a sensor, which uses distance measurement via optical triangulation as the basic method. For special robot tasks, special mechanical and hardware arrangements of the basic sensor type are needed. Two examples are shown for demonstration purposes. Possible applications are simple distance sensor devices, two-dimensional orientation sensors and optical robot teach-in units. Accuracy and efficiency of the sensor system are documented by using the sensor for recognizing holes and following arbitrary unknown contours.

Keywords. Position measurement; computer peripheral equipement; optical distance sensors; robot teach-in.

INTRODUCTION

Progress and further development in robot assembly tasks will be inclose relationship with new sensor technologies. Sensory information enables an assembly robot to perform systematic movements referenced to arbitrary operational objects.
Due to the fast processing of the sensory systems information, in comparision with image processing systems, optical proximity sensors will become a very important part of the technological development of low-cost sensors. The variety of optical proximity sensors leads from simple reflex-couplers to line-sensors similar to image processing systems as shown in [1].
The paper presents the sensory design principles using position sensitive semiconductor devices and the measurement methods utilizing these devices e. g. triangulation. The major problem of optical distance measurement is the dependence of the object-reflected light on the surface and orientation of the object, and the decrease of light intensity with the square of the object's distance. Experiments to control the light intensity by adapting the output power of the light emitting diode, shown in the publications of [3] and [4], enlarged the maximum range successfully. Using diffuse reflected light of a very narrow focused light beam delivers the measurement from influence on object's surface or orientation.
Appropriate microcontrollers make a fast signal processing possible (> 1 kHz).

STRUCTURE OF BASIC OPTICAL PROXIMITY SENSOR DESIGN.

The goals of robot-sensor development are on the one hand cost-effectiveness and flexibility and on the other hand robustness against mechanical and environmental influences. For this reason the proximity sensor principle published here uses a focussed infrared lightbeam at a wavelength of 950 nm coming from an infrared light emitting diode and reflected at the remote object.
Two main reasons make the use of laser devices impossible. On the one hand a laser doesn't accomplish the required dimensions, and on the other hand a laser beam endangers human eye.
Because of the roughness of the surfaces of most of the assembly-object surfaces the narrow lightbeam is diffusely reflected. A part of the reflected light falls on an optical lense and is focussed as a spot on the surface of a position sensitive semiconductor element. The edge currents of the spot-position-detector are used to evaluate the maximum of the spot position.

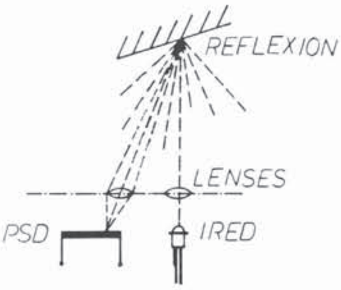

FIG. 1. Incidence of rays

The light-spot generates a photo-current which is devided into two position detector edge-currents with values inversely proportional to the distance between spot-position and detector edge.

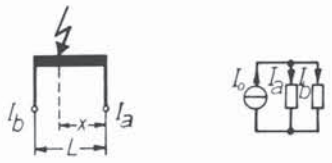

FIG. 2. Edge-currents

The following equations can be obtained by geometrical considerations:

$$(1)\quad I_a = I_o \cdot \frac{R_o \frac{L-x}{L}}{R_o} = I_o \cdot \frac{L-x}{L}$$

$$(2)\quad I_b = I_o \cdot \frac{R_o \frac{x}{L}}{R_o} = I_o \cdot \frac{x}{L}$$

$$(3)\quad \frac{I_a}{I_b} = \frac{I_o \cdot \frac{L-x}{L}}{I_o \cdot \frac{x}{L}} = \frac{L-x}{x}$$

$$(4)\quad x = \frac{L}{(1+\frac{I_a}{I_b})} = L \cdot \frac{I_b}{I_a+I_b}$$

The result of the division of the two edge-currents I_a and I_b is leading to the light spot position x and doesn't depend on the light intensity I_o. Therefore the measurement procedure becomes independent from the object's surface, color and orientation, as long as the intensity of the reflected light is high enough. However, experiments have shown that the theoretical independence from object's orientation and light intensity will only be satisfied if the object's surface is a real diffuse reflector. In [2] the application of a number of infrared diodes around the position-sensitive-detector improves the measurement accuracy for which one pays, however, by a reduced distance range and a higher amount of hardware.

Because of the jamming of environmental illumination changes, the analog edge-current signal processing is very complicated too. For this reason four general steps are necessary. At first the emitting-power of the infrared diode has to be controlled, to reduce the decrease of light intensity for larger distances. The analog PI-controller applied here varies from the method of digital approximation control as shown in [2], beeing more simple. To distinguish the useful edge-currents from enviro-mental interferences the emitted light has to be modulated and the edge-currents have to pass through an analog bandfilter. Finally an optical infrared-filter is put in front of the collector lense, similar to those published in [1] and [3].

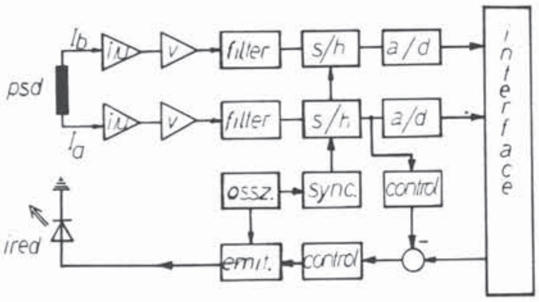

FIG. 3. Blockdiagram

The preprocessed analog signals are sampled and converted to digital values. The microcomputer is now able to perform the following tasks.

The edge-current values pass through a digital low-pass filter according to the software realization of equation (4).

$$(4)\quad x = L \cdot \frac{I_b}{I_a + I_b}$$

Depending on the geometrical assumptions, the result x of the division is assigned to the desired distance d. In the simplest case this assignment is expressed by the equation

$$(5)\quad d = const \cdot \frac{1}{x} ,$$

but in most sensor applications varying in geometrical and optical dimensions, the assigment

$$(7)\quad d = f(x)$$

is better performed in a look-up-table. Therefore this solution was chosen finally. The distance d is checked on plausibility. The maximum velocity between robot and object leads to the maximum change of the distance value in one cycle. The microcomputer has to ensure that all values are between the minimum and maximum distances fixed by the geometrical assumptions. Modulation and sampling of analog signals fix the period to be

$$(8)\quad t_{anl} = \frac{1}{f_{mod}} .$$

A modulation frequency f_{mod} of 10 khz leads to an analog sampling period of 100 microseconds. In this time the microcomputer has to do digital-filtering, plausibility checks and distance assignment. Even with the time cycle of modern robot con trol systems a new sensory value has to be generated once every millisecond only. Therefore up to twenty distance values can pass through a digital low-pass filter or can be averaged by special algorithms.

HARDWARESTRUCTURE

The basic requirements for the integration of sensory devices into robot control systems is a flexible digital interface with standard hardware components. Standardized low- and high-speed serial and parallel interfaces must be provided when the sensory signal processing is done by sensory processors and not by robot control systems. Such a concept is developed in the frame ARC (Advanced Robot Control) shown in [8], where each sensor processsor is interfaced via dual-port memory chips to the robot control. This concept of one sensor-processor (8088) can integrate various sensors of similar type depending on the complexity of the corresponding algorithms. An alternative, which is now under realization, is to use one microcontroller (e.g. 8051) for each sensor, where a serial interfacing (low- or high-speed) will be used. A characteristic feature of a "smart-sensor-system" is the "stand-alone" structure of the implemented higher level operations. A stand-alone microcomputer smart-sensor-system with RS 232 serial interface with this items was developed at the THD system theory robot lab.

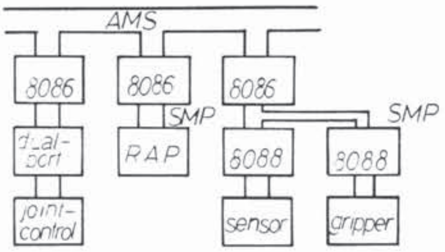

FIG 4. Hardwarecomponents ARC

The various types of hardware structures shown here will solve most of the sensor-system configuration problems by transfering the algorithms from one system to another.

ALGORITHMS

The result of the analog-digital-converting is a 16 bit word from which only the upper ten bits are used. In most applications also the upper nine or eight bits are sufficient. These integer values are converted into the standard 32 bit floating point format and pass through a digital low pass filter to eliminate high-frequency noises.

$$(9) \quad I_{j_{out}}(k) = -a_1 I_{j_{out}}(k-1) + b_0 I_{j_{in}}(k).$$

The following computation of the spot-position on the position-sensitive line is done with equation (4).

$$(4) \quad x = L \frac{I_b}{I_a + I_b}$$

by assigning a 32 bit floating point value to the variable x. An integer operation converts this floating point number into an integer value to address the look-up-table input x_{INT} of equation (7).

$$(7) \quad d_{INT} = f(x_{INT}).$$

If necessary, the successive values $d_{INT}(s)$ will pass through a second low-pass digital filter

$$(10) \quad d_{OUT}(k) = -a_1 d_{OUT}(k-1) - \dots \\ -a_n d_{OUT}(k-n) \\ +b_0 d_{IN}(k) .$$

If the parameters $-a_1 \dots -a_n$ and b_0 have the value $1/n+1$, the equation is equivalent to an averaging algorithm. Adapting these parameters to the special application leads to a sensor information free of disturbing noises and unreasonable values. Unlike the methods published in [3] and [4] the higher level signal-processing is here completely digital and this gives the user the opportunity to vary the filter-algorithms and extend the signal-processing with plausibility-checks.

VARIATION OF THE BASIC SENSOR DESIGN

In all sensor applications the basic principle described in chapter one is the major part of the various sensor types. The proximity sensor based on triangulation produces a distance information nearly independent from the object's orientation or surface. The construction is similar to the publication [3] or [4].

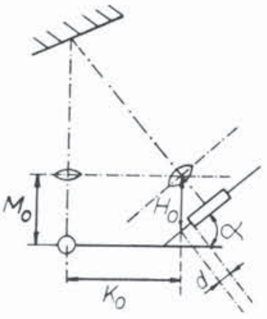

Fig. 5. Distance sensor

The geometrical sensor set-up leads to the equation :

$$(11) \quad d = H_0 K_0 \cdot \frac{1}{\cos \alpha} \cdot \left[\frac{1}{x - b} - \frac{\sin \alpha}{H_0} \right].$$

In this case α is the triangulation-angle. In the simplest version α and b are zero,

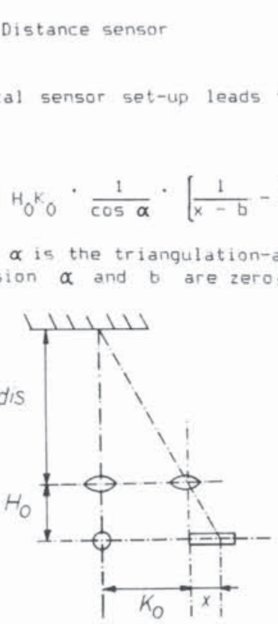

Fig. 6. Standard distance sensor.

which leads to the equation

$$(12) \quad d = \frac{H_0 K_0}{x}.$$

A type of this distance sensor was built up in the THD robot lab and leads to a measuring range of 50mm - 300mm with an accuracy of 0.5% at a distance of 100 mm. This application can be used in various robot tasks like following a moving object along the optical axis of the distance sensor. The distance between a sensor mounted on the robot-endeffector and an object is measured and used as the actual value in the distance contol-loop of the robot control system.

Fig. 7. Following moving objects

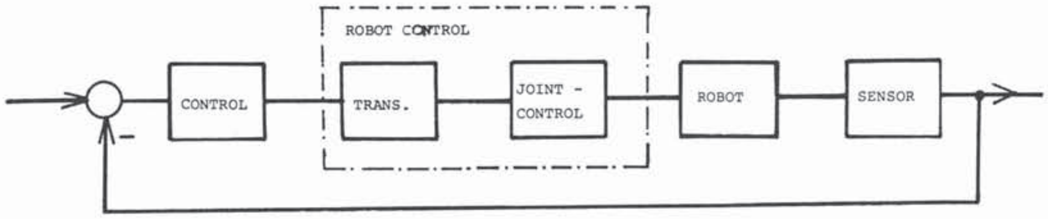

Fig. 8. Distance-control-loop.

By using two or more infrared emitters, the sensor will be capable of finding the orientation of an object.

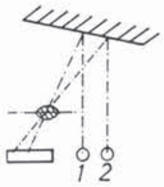

Fig. 9. Measuring object's orientation.

Determining the orientation of an object can be useful to prevent gripping of a wrongly oriented object, thereby loosing or damaging it. An arbitrarly oriented object lying on a working platform is gripped parallel when using an orientation sensor.

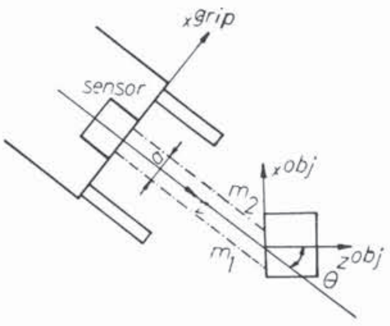

Fig. 10. Object orientation relative to gripper orientation.

The two emitter-rays, m_1 and m_2, give the orientation angle θ^{OBJ} and the average distance z^{OBJ}.

$$(13) \quad z^{OBJ} = z^{GRIP} + \frac{m_1 + m_2}{2}$$

$$(14) \quad x^{OBJ} = x^{GRIP}$$

$$(15) \quad y^{OBJ} = y^{GRIP}.$$

Therefore, the first step is a coordinate transformation from the coordinate frame $\underline{X}^{GRIP}$ to the frame $\underline{X}^{OBJ}$, which is equivalent to shifting along the z-axes by $\frac{m_1 + m_2}{2}$. The second step is a rotation about the new axis $Y^{GRIP} = Y^{OBJ}$ through an angle

$$(16) \quad \theta^{OBJ} = \arctan \frac{m_1 - m_2}{a}.$$

Gripping an object means then rotating the gripper in Z-X coordinate plane about the Y^{OBJ}-axes through the orientation angle θ^{OBJ} and then moving along the Z-axis with the distance z^{OBJ}.

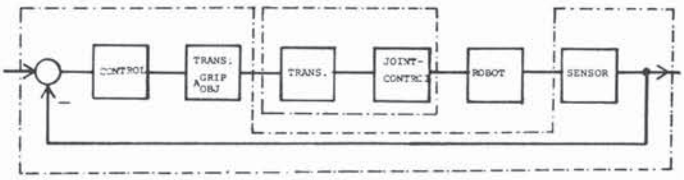

Fig. 11. Control loop for orientation control

A more complex extension of this method is to use four infrared diodes around a two-dimensional position sensitive detector. This gives the robot control the opportunity to measure the object's orientation in two dimensions. The two-dimensional position sensitive detector has the same features as the one-dimensional sensor. Because of this the corresponding hardware is the same as described in chapter one.

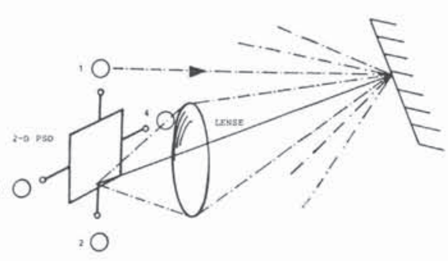

Fig. 12. Two-dimensional orientation measuring

The geometrical set-up leads to two angles θ^{OBJ} and ψ^{OBJ} calculated out from the four emitted rays $m_1 \dots m_4$.

$$(17) \quad \theta^{OBJ} = \arctan \frac{m_1 - m_2}{a}$$

$$(18) \quad \psi^{OBJ} = \arctan \frac{m_3 - m_4}{a}.$$

Gripping the object means now rotating the gripper in the X-Y-plane through θ^{OBJ} and in the Y-X-plane through ψ^{OBJ} about the coordinate $\underline{X}^{OBJ}$.
The last variation of the basic sensor principle leads to an optical teach-in device. The basic idea is letting the robot follow the motion of an optical spot describing the path to be programmed.

The robot follows the visible and infrared light-beam combination of an equipment in the users hand. The infrared light is scattered by a special optical lense and therefore is equivalent to the scattered reflection of the light beam in the distance sensor device. A part of this light finds its way through an optical infrared filter and an optical lense, focusing the light as a small spot on a two-dimensional position sensitive detector. The spot-position, calculated from the four edge-currents of the detector, is then used by the tracking algorithm in the robot control system.

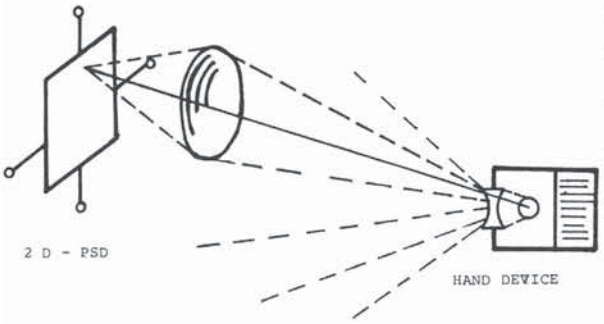

Fig. 13. Optical teach-in

The algorithm which assigns a robot motion to the spot position is very simple.

```
(19)  IF $|I_{j+} - I_{j-}| > I_{IMOV}$ THEN
          IF $I_{J+} > I_{J-}$ THEN MOVE IN DIRECTION j
          ELSE MOVE DIRECTION -j
      ELSE DO NOT MOVE
```

SENSORAPPLICATIONS

To demonstrate the advantages of the sensor-system, four applications are described here. At first a single-distance sensor is used to follow an unknown arbitrary contour. The distance $z^{contour}$ between the sensor-guided robot and the reflection-point of the contour is held on a nominal value of 120 mm by moving the robot in Z-direction vertical to the movement along the X-axis.

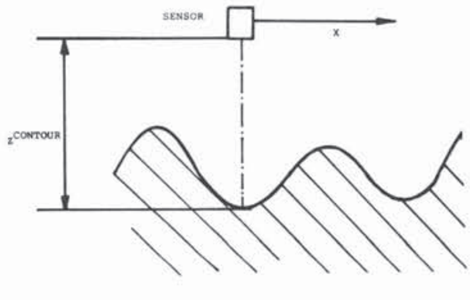

Fig. 14. Following an unknown contour

The $z^{contour}$ sensor control-loop is similar to the control-loop of following moving objects. Because of the integrating behaviour of the process, especially of the internal joint controllers, only standard P- or PD-controllers can be used. The PD-controller is droped out because the differentiating behaviour is disadvantageous on the presence of noise. A standard P-controller calculates the difference between the desired value $z^{contour}_{nom}$ and the actual value $z^{contour}$. The following diagrams document the actual distance value $z^{contour}$ along the contour with various P-values K of the contour-following control-loop.

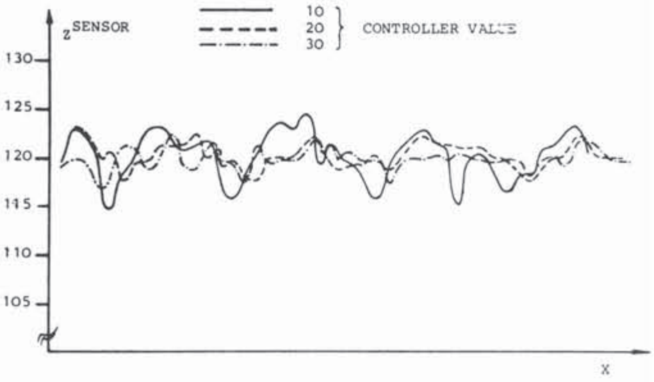

Fig. 15. Contour following diagram

A second tested application is using the single-distance sensor for hole recognition in a plane environment. The robot performs a linear movement along the X-axis and the distance value in Z-direction is registered.

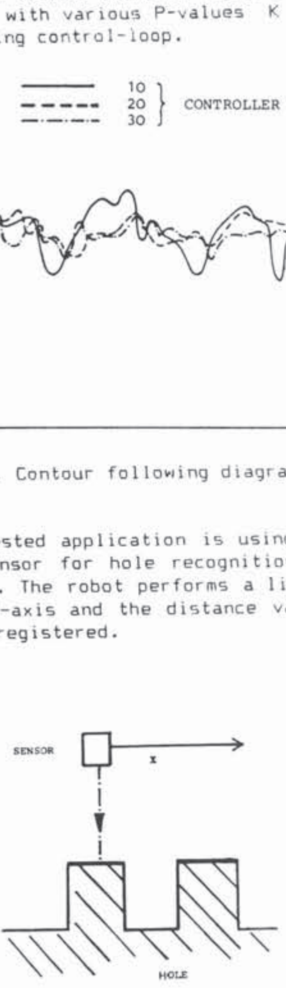

FIG 16. Hole recognition

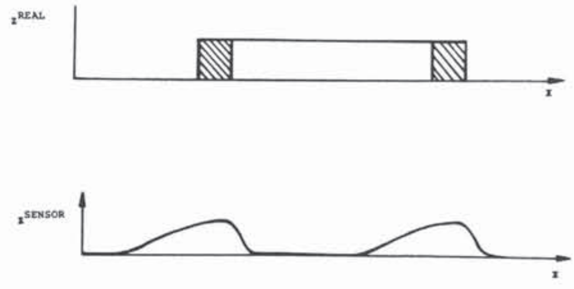

FIG 17. Sensor value

A third possible application uses a combination of three single-distance devices mounted in a u-formed endeffector to follow the sharp edge of an assembly plate.

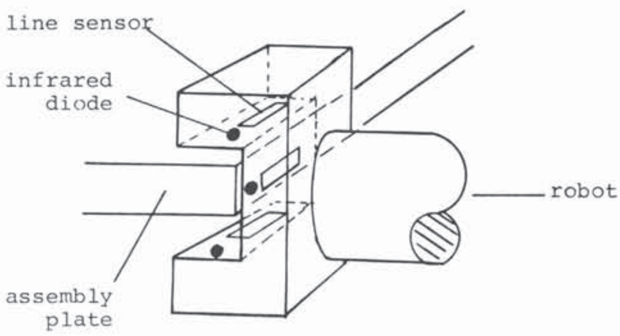

FIG 18. Edge-following endeffector

A last very promising application is a three-dimensional sensor-cube to measure the dynamic behaviour of the robot endeffector-tip. The sensor cube is provided with three orthogonal mounted two-dimensional position sensitive areas. This complex sensor device is able to measure small dynamic missalignments of the robot endeffector-tip after reaching a desired teached position, by using six space fixed infrared diodes as cartesian position reference.

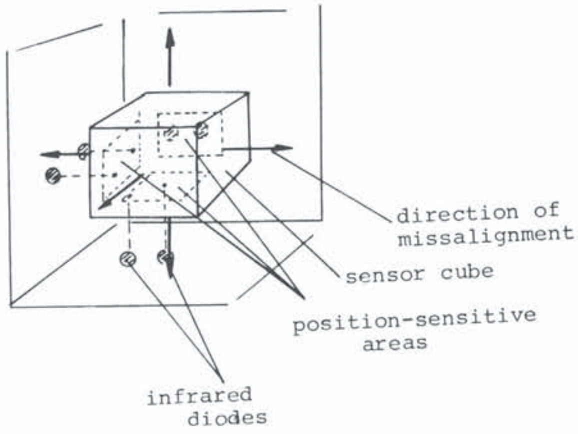

FIG 19. Dynamics measurenment

CONCLUSIONS

Basic design principles and some of the possible extensions and advantages of optical proximity sensor systems are discussed. As a low-level vision system they can be integrated in various robot tasks very effectively. Due to the fast signal processing they can be integrated in real-time control loops utilizing low- and mid-range enviromental information with respect to the endeffector. Further developments are expected in five major areas.
On the one hand the sensor equipments will become smaller in size and the analog signalprocessing will be integrated in the sensor head. The optical lenses and filters will be replaced by special microlenses. On the other hand new sensor combinations will be designed for special applications. Furthermore the sensor devices will be integrated into multisensor grippers together with reflex-coupling matrices, gripping-force sensors and slip sensors to detect the behaviour of a gripped object. Moreover the accuracy of the sensor system will be improved to values better than the repeatability accuracy of the mechanical robot system. Finally hierarchies of often redundant multisensor information structures will be a major requirement for complex robot assembly systems. However, all robot assembly requirements couldn't be fulfilled by one universal sensor. The various applications will still require a number of different solutions. A small number of the possible sensor applications is presented here.

REFERENCES

[1] KEMPKENS, K. AND BECKER, N.
REGELUNG VON ROBOTERBEWEGUNGEN AUFGRUND OPTISCHER ABSTANDSMESSUNG.
VDI/VDE GESELLSCHAFT MESS- UND REGELUNGSTECHNIK
STEUERUNG UND REGELUNG VON INDUSTRIEROBOTERN
12./13.5.1986 LANGEN/FRG

[2] KANADE, T. AND SOMMER, T.
AN OPTICAL PROXIMITY SENSOR FOR MEASURING SURFACE AND ORIENTATION FOR ROBOT MANIPULATION.
ROBOTICS RESEARCH 1984

[3] HIRZINGER, G. AND DIETRICH, J.
SENSORSYSTEM FüR ROBOTER.
VDI AUSSPRACHETAG
SIGNALVERARBEITUNG IN MULTISENSORSYSTEMEN
18./19.2.1986 KARLSRUHE/FRG.

[4] DIETRICH, J.
OPTISCH-ELEKTRONISCHER ENTFERNUNGSMESSER.
PATENT P 3502634.0 ANGEMELDET

[5] KONSTANTAS, A.
ERWEITERUNGEN AN DER SIGNALVERARBEITUNG EINES OPTISCHEN DISTANZSENSORS.
DIPLOMARBEIT 1986
TECHNISCHE HOCHSCHULE DARMSTADT FRG

[6] BARZ, R.
OPTISCH ELEKTRONISCHER SENSOR ZUR MESSUNG VON OBJEKT-ORIENTIERUNGEN IN ROBOTERMONTAGE AUFGABEN.
DIPLOMARBEIT 1986
TECHNISCHE HOCHSCHULE DARMSTADT FRG

[7] KEGEL, G.
AUFBAU VON OPTISCHEN NäHERUNGSSENSOREN FüR SENSORGESTüTZTE ROBOTERMONTAGE AUFGABEN.
STUDIENARBEIT 1985
TECHNISCHE HOCHSCHULE DARMSTADT FRG

[8] E.ERSü, K.RATHGEBER, M.SCHNELL, W.NEDDERMEYER
A ROBOT ARITHMETIC PROCESSOR CONCEPT FOR CARTESIAN CLOSED-LOOP CONTROL WITH PRESCRIBED DYNAMICS.

PROC. OF THE 1st IFAC SYMPOSIUM ON ROBOT CONTROL, NOVEMBER, 6-8, 1985, BARCELONA