Offset Compensation Method Using Photoelectric Switches for Positioning Control System[†]

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An offset compensation method using reflection-type photoelectric switches is studied with the aim of achieving a low-cost and highly accurate positioning control system. This system uses an open-loop control type robotic mechanism consisting of pulse motors and ball screws to reduce the cost. To make an optical connection in an automated optical cross-connect switching system, the robot must position optical fiber plugs at desired positions. The "on" region of the photoelectric switches is determined by scanning the plug grasped by the robot hand in front of the photoelectric switches. Offset compensation is achieved by calculating the difference between the initial position of the center of the region and the newly measured value. Experimental results show that the repetition error of the offset detection is less than 5 μm (about 0.1% of the control position pitch) and the position variation of the center of the "on" region is less than 30 μm when the distance between the switch and the plug is 0.1–1.0 mm. The feasibility of this compensation method using photoelectric switches was confirmed by installing it into the automated optical cross-connect switching system.

Key Words: photoelectric switch, offset compensation, robot, positioning control

1. Introduction

Recently a small, high-precision robotic mechanism has been made through mechatronics. It became possible mainly as a result of high-speed signal processing by microcomputers and high-performance actuators^{1),2)}.

It is effective to use an open-loop control type robotic mechanism consisting of pulse motors and ball screws because of their low cost and small size. Therefore, we applied this mechanism to an automated optical cross-connect switching system^{3)~5)}, which cross-connects the selected optical-subscriber cable with the desired optical-office-equipment cable. The robot in the automated optical cross-connect switching system controls the connection/disconnection of the optical fibers as it inserts a plug with a fiber into the fiber adaptor on the adaptor alignment board or removes one from the adaptor. The problem is that it is difficult to move the robot hand to the target position precisely when thermal expansion occurs or the positions of the mechanical origins change, because the motor coordinates do not coincide with the target coordinates that were fixed in advance. If the ambient tempera-

ture varies by 30 degrees, the 250 $\times$ 200 mm adaptor alignment board expands by about 0.1–0.2 mm in the case of non-uniform expansion between the robot mechanism and the adaptor alignment board. In the worst case the robot hand fails to reach the target position and cannot connect the fibers properly, because the target position is not sensed.

One proposal for decreasing the position error is to control the robot hand precisely by detecting the target position with a CCD (charge coupled device) sensor⁶⁾ or a PSD (position sensitive device) sensor⁷⁾. However, it is difficult to locate the CCD or PSD sensor at the small tip of the robot hand. Moreover, the sensor and signal processing circuits for it are expensive.

The other proposal⁸⁾ is to detect the position of the robot hand relative to the target positions (i.e. shelves in the optical disk cartridge storehouse) using photoelectric switches in the robot hand and reflection marks formed on the front surface of each target. However, this system cannot compensate for the mechanical variation from the photoelectric switches to the optical disk cartridge being grasped by the hand, and the robot hand becomes larger and more complicated mechanism because of installing photoelectric switches.

In order to obtain a low-cost, highly accurate positioning control for an optical fiber handling robot, we studied an offset compensation method using simple and small photoelectric switches. The photoelectric switches are

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installed in an adaptor alignment board. The positions of the photoelectric switches are determined by scanning the plug grasped by the robot hand in front of the photoelectric switches. This paper describes the principle of this method, presents results of measuring the characteristics, and shows the effectiveness of adopting this method to the automated optical cross-connect switching system.

2. Mechanical Configuration of the Robot

Figure 1 shows the configuration of a positioning system for a fiber handling robot and the arrangement of photoelectric switches in an adaptor alignment board. The robot consists of a hand, three pulse motors, and three-axis mechanical guides with ball screws. The robot controls the connection and disconnection of the optical fibers by inserting a plug with a fiber into the fiber adaptor on the adaptor alignment board or by removing one from the adaptor. In this plug connection/disconnection procedure the robot hand is controlled by the x , y , and z -axis pulse motors with an open-loop (without feeding back the photoelectric switch signals). A ferrule is set on the tip of the plug, and there is a hole for the ferrule in the center of the adaptor. The plug with a fiber is connected to the adaptor by inserting the ferrule of the plug into the hole in the adaptor.

Figure 2 shows the arrangement of photoelectric switches and the adaptor alignment board. The adaptor alignment board contains many small holes for the

Fig. 1 Configuration of positioning system for a fiber handling robot and arrangement of photoelectric switches

adaptors in a precise regular pattern. Two reflection-type photoelectric switches are buried in the holes set at diagonally opposite corners on the adaptor alignment board.

3. Compensation Method

Once the positions of the two holes at diagonally opposite corners on the adaptor alignment board have been measured using photoelectric switches, as described in section 3.1, all the other hole positions in the adaptor alignment board can be calculated by interpolation with the assumption that a temperature change causes linear and isotropic movement of the adaptor alignment board.

3.1 Detection of hole center

The reflection-type photoelectric switch can detect light reflected from a target object and outputs an "on/off" signal according to the reflected power. That is to say, the photoelectric switch outputs the "on" signal when the target object approaches it and the power entering the detection fiber exceeds the threshold level for an "on" state. In our experiment, the target object was a ferrule, which is the tip of an optical plug.

In the offset compensation procedure the robot hand grasping the plug with the ferrule approaches the photoelectric switch head to within about 1 mm and scans the plug by small step movements along the x and y -axes in the plane perpendicular to the hole of the adaptor. The robot detects two transition positions as the signal changes from "off" to "on" and from "on" to "off" when the robot scans along each axis. The center of the "on" region is calculated as the position midway between the two transition points at each scan.

Figure 3 shows the calculation method for detecting the "on" region of the photoelectric switch. The circle is the

Fig. 2 Arrangement of photoelectric switches and an adaptor alignment board

Fig. 3 Calculation method for detecting "on" region

border that separates the "on" region from the "off" region.

First, according to the internal counter of the CPU, the robot grasping the ferrule of the plug positions the hand at point A, i. e. the starting point for x -axis scanning. The internal counter, which has more than 24 bits, is composed of the IC memory (RAM) of the CPU and is controlled by the robot movement program. Point A is located slightly before the "on" region considering the maximum change in size of the adaptor alignment board with change in temperature. Because the maximum size change is assumed to be 0.1–0.2 mm, point A should be set more than 0.6 mm ("on" region radius 0.4 mm + 0.2 mm) away from the previously preset center point of the photoelectric switch. The robot scans in the positive direction of the x -axis step by step with the x -axis pulse motor, counts the number of steps as pulse number, and checks the state of the output signal of the photoelectric switch to see whether the signal is "on". The point a is measured using the unit of the step pulse number of the x -axis pulse motor from the starting point A for the x -axis. If the signal is "off", the robot continues to scan another step until the signal is "on". When the signal becomes "on" at point a , the pulse number from the starting point A to point a is sent to the CPU and stored.

The robot continues to scan along the x -axis until the state of the signal is "off". When the signal becomes "off" at point b , the pulse number from the starting point A to point b is sent to the CPU and stored. The detection precision can be improved by making several scans at different places for each axis. Similarly, the points e to h are measured using the pulse number of the y -axis pulse motor.

By using the internal counter the robot controls the movement of its hand to the starting point for the other switch that is located at the diagonally opposite corner on the adaptor alignment board as in the former method. The

Fig. 4 Block diagram of offset detection circuit

starting point is determined by the preset center position renewed by the latest offset measurement results and also scans along the x -axis and the y -axis.

In this figure the center point X_c for the x -axis is calculated from

$$X_c = (a + b + c + d) / 4,$$

and the center point Y_c for the y -axis is similarly

$$Y_c = (e + f + g + h) / 4.$$

The center point of the "on" region is determined by measuring at least three transition points because a circle is defined by three points. We actually made eight measurements in order to get high precision (i. e. less than 20 μ m).

If in advance, the real hole center and the center of the "on" region are measured at the same time, the new hole center shifted by temperature change can be calculated from the new measurement of the center of the "on" region by using this relation. In this calculation it is assumed that the change in size of the adaptor alignment board is linear and isotropic due to expansion, rotation and displacement.

It is necessary to use this offset compensation method when the plug connection/disconnection operation fails due to positioning error of the robot hand or when the mechanical components of the robot are renewed. Therefore, in the case of the usual plug connection/disconnection operation, it is not necessary to use the offset compensation procedure, but the robot controls the hand according to the latest offset results achieved.

3.2 Detection circuit

Figure 4 shows the block diagram of the offset detection circuit. The robot hand is controlled by the x -axis pulse motor and the y -axis pulse motor. The motor driving pulses from the controllers are selected and counted. The

Fig. 5 Flow chart for detecting the center of the “on” region

pulse counts are stored in two registers, one for the “on” point, and the other for the “off” point. The counter and the registers have 8-bit resolution. Therefore, the scanning distance of the robot hand for the offset measurement is about 2.5 mm, because the step distance of the pulse motor is 10 μm. The scanning distance is sufficient when it is longer than 2 mm, because the diameter of the “on” region is about 0.8 mm. The data stored in the registers is transferred to the CPU through the I/O port, and the control signals for the counter, selectors, etc. are output by the CPU through the I/O port.

3.3 Flow chart of measurement procedure

Figure 5 shows the flow chart for detecting the center point of the “on” region. In this flow it is not necessary to use a counter and register circuit as shown in Fig. 4. This procedure reduces the hardware cost, but the measurement time of this procedure becomes longer than that of the method in Fig. 4. The CPU checks whether the state of the photoelectric switch is “on” or “off”. If the state is different from that in the previous step, the step numbers *N* and *M* from the initial point *A* to the transition position are recorded in the CPU. The center point of the “on” region for the *x*-axis is calculated from the numbers *N* and *M*. Similarly, the center point for the *y*-axis is calculated by scanning the hand along the *y*-axis.

4. Characteristics of “on” Region

4.1 Experimental setup

Figure 6 shows the experimental arrangement for measuring the switching characteristics. The top surface of the ferrule for the optical plug was used as the reflection object for the photoelectric switches. The plug is consisted of the cylindrical ferrule and the metallic holder that supports the root of the ferrule. The plug was an MU-type

Fig. 6 Experimental arrangement for measuring switching characteristics

Table 1 Specifications of a photoelectric switch and a target object

Photoelectric switch	Detection type	Reflective type (not through-beam type)
	Light source	Red LED light (660 nm)
	Output response time	250 μs
	Maximum detection distance for 10 mm × 10 mm white paper	4 mm
	Smallest detectable object	15 μm φ copper wire
Target object	Object	Top surface of ferrule
	Reflection surface	Polished surface of 0.5 mm φ

Photo. 1 Microscopic photograph of a photoelectric switch head

optical connector with a ferrule 1.25 mm in diameter. The surface of the ferrule that is made of ceramics, was polished precisely.

The plug was fixed on a three-axis movable table and located in front of the photoelectric switch. We measured the “on” and “off” positions of the photoelectric switch by moving the plug. The measurement precision was 10 μm. Table 1 shows specifications of the photoelectric switch and the target object. Photo. 1 shows the photoelectric switch head containing two fibers, one for the light source,

the other for the light detection. The red light of 660 nm is emitted from the light source fiber installed in the head of the photoelectric switch and is reflected from the plug surface. The photoelectric switch head is connected to the switch amplifier by an optical cable.

4.2 Experimental results

(1) "on" region

Figures 7, 8 and 9 show measurement results for the "on" region when the distance Z between the ferrule of the plug and the photoelectric switch was changed from 0.1 mm to 0.8 mm. The amplifier gain G of the photoelectric switch for Fig. 7 is 0.75, for Fig. 8 is 1.25 and that for Fig. 9 is 1.75. Symbols such as "#", "\$" etc. represent measured values of "on" or "off" transition positions and circles show the trend in the measured values in these figures. The gain G is shown as the rotation number of the variable resistance for the amplifier of the photoelectric switch. When the gain G increases, the photoelectric

switch outputs the "on" state even when the reflected light power the weaker. That is to say, the threshold level for the "on" state of the photoelectric switch decreases for higher gain of the amplifier. In Fig. 7, the outermost circle is for $Z=0.3$ mm, the middle one is for 0.7 mm, and the innermost one is for 0.8 mm. In Fig. 8, the outermost circle is for $Z=0.3$ mm, the middle one is for 0.1 mm, and the innermost one is for 0.8 mm. In Fig. 9, the outermost circle is for $Z=0.3$ mm, the middle one is for 0.9 mm, and the innermost one is for 1.1 mm.

Figures 7-9 show that the diameter of the "on" region is about 0.8 mm. Therefore, it is effective if the robot hand scans at least 2 mm around the center of the photoelectric switch for the offset measurement. Moreover, they show that the measured values almost coincide with the exact circular lines. Therefore, we estimate that the light beam emitted from the photoelectric switch is also circular. Figure 7 indicates that the circle enclosing the "on" region decreased in diameter and the center of the "on" region shifted right and down when the distance Z increased. But when the gain G is 1.25 the center of the "on" region hardly shifts (less than $\pm 20 \mu\text{m}$) from $Z=0.1$ mm to 0.8 mm. Even if the diameter of the "on" region changes, the center position of the "on" region will not change, when there is no shift of the "on" region. This phenomenon increases the detection margin. When the gain G is 1.75 the variation in the detection of the center position of the "on" region is about $30 \mu\text{m}$ from $Z=0.1$ mm to 1.0 mm.

(2) Detection margin

There is a variation in the distance between the photoelectric switch and the ferrule of the plug because of the positioning error of the robot and expansion of adaptor alignment board due to temperature change, when the robot moves the plug in front of the photoelectric switch. Therefore a wide detection margin is useful.

Figure 10 shows the detection margin for the distance

Fig. 7 Measurement results for "on" region at $G=0.75$

Fig. 8 Measurement results for "on" region at $G=1.25$

Fig. 9 Measurement results for "on" region at $G=1.75$

Fig. 10 Detection margin for distance along z-axis

Fig. 11 Histogram of repetition error for offset measurement

along the z-axis versus amplifier gain G . The gain G is set to 0 when the photoelectric switch just changes to the "off" state from the "on" state at the target position of the nominal distance ($Z=0.6$ mm) with gradually decreasing gain. When the gain G is 5, the photoelectric switch just changes to the "on" state even if there is no target near the switch. This figure shows that the detection margin increases with gain of the photoelectric switch. For $G=1.75$, the detection margin is about 0.9 mm.

(3) Detection error

We measured the detection error as variation of the offset measurement values for the same experimental conditions. That is to say, the detection error represents the repetition error. Figure 11 shows a histogram of the repetition error in the measurements made by the cross-connect switching robot that can jumper optical fibers. The robot controls the hand by 10-μm steps and makes two scans in the same direction for each axis in order to reduce the measurement error. The two scans are about 0.1 mm apart.

The x - y - z table is supported by linear guides and ball screws as shown in Fig. 1. The parallelism error of the linear guides for the x , y , and z axes is less than 3 μm, the axial spacing of the ball screws for each axis is less than 5 μm, and the lead pitch error is less than 10 μm for the full stroke.

Photo. 2 Arrangement of a photoelectric switch head installed in the automated optical cross-connect switching system

In Fig. 11 the horizontal axis shows the repetition error of the offset detection and the vertical axis shows the frequency of the error. The total number of measurements was 40, the average repetition error of the offset detection was about 4.3 μm (about 0.1% of the control pitch), and the standard deviation was 4.3 μm. Therefore, the positioning error of all adaptors in the adaptor alignment board is considered to be below the target error of 20 μm because the table precision error is less than a few micrometers.

(4) Effectiveness for automated optical cross-connect switching system

Photo. 2 shows the arrangement of a photoelectric switch head installed in an automated optical cross-connect switching system with 2000 adaptors and 1000 plugs. The adaptors are located in a rectangular lattice of 4×6 mm on the adaptor alignment board. The compensation method as shown in Fig. 5 is used in the automated optical cross-connect switching system. It took about 70 seconds to finish the compensation procedure with two scans in the same direction for each axis at a pair of diagonal measurement points including the travel time to the measurement points from the origin point and the rise and fall time of the robot hand. That is to say, a total of eight measurements of "on" to "off" or "off" to "on" transition points were accomplished. This compensation method was very effective when the robot hand was changed because there was no need to recheck or remeasure the reference points precisely. Moreover, a fiber handling robot using this offset compensation method has operated for about one year without any problems.

This offset compensation system cannot be adapted only to the pulse motor control system but also to an AC servo motor control system that feeds back the motor encoder

signal to the motor.

5. Conclusions

Offset compensation using reflection-type photoelectric switches should lead to a low-cost, highly accurate positioning control system. This system is necessary for a robotic mechanism that must position many identical objects such as electrical parts at desired positions.

The robot hand grasping an object (a plug for an optical fiber) scans in front of photoelectric switches and determines the "on" region. The center of the region is determined from the "on" region of the photoelectric switches. Offset compensation can be achieved by calculating the difference between the initial position of the center of the region and the newly measured value.

The experimental results show that the repetition error of the offset detection is less than $5\mu\text{m}$ (about 0.1% of the control position pitch) and the position variation for the center of the "on" region is less than $30\mu\text{m}$ when the distance between the photoelectric switch head and the ferrule of the plug is 0.1 mm to 1.0 mm. The effectiveness of the compensation method using photoelectric switches was confirmed by installing it into an automated optical cross-connect switching system and controlling the robot to exchange plugs.

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