The Performance Improvement of a Linear CCD Sensor Using an Automatic Threshold Control Algorithm for Displacement Measurement

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Abstract: Among the sensors mainly used for displacement measurement, there are a linear CCD(Charge Coupled Device) and a PSD(Position Sensitive Detector) as a non-contact type. Their structures are different very much, which means that the signal processing of both sensors should be applied in the different ways. Most of the displacement measurement systems to get the 3-D shape profile of an object using a linear CCD are a computer-based system. It means that all of algorithms and mathematical operations are performed through a computer program to measure the displacement. However, in this paper, the developed system has microprocessor and other digital components that make the system measure the displacement of an object without a computer. The thing different from the previous system is that AVR microprocessor and FPGA(Field Programmable Gate Array) technology, and a comparator is used to play the role of an A/D(Analog to Digital) converter. Furthermore, an ATC(Automatic Threshold Control) algorithm is applied to find the highest pixel data that has the real displacement information. According to the size of the light circle incident on the surface of the CCD, the threshold value to remove the noise and useless data is changed by the operation of AVR microprocessor. The total system consists of FPGA, AVR microprocessor, and the comparator. The developed system has the improvement and shows the better performance than the system not using the ATC algorithm for displacement measurement.

Keywords: CCD, Comparator, ATC, Displacement Measurement

1. INTRODUCTION

Among the sensors mainly used for displacement measurement, there are a linear CCD(Charge-Coupled Device) and a PSD(Position Sensitive Detector) as a non-contact type. Their structures are different very much, which means that the signal processing of both sensors should be applied in the different ways. In case of PSD, it has some disadvantages like sensitivity to environmental lights and nonlinearities. In addition, a CCD has some limits in resolution and speed because of its structure, and it needs a complex image-processing algorithm. However, a CCD is more robust to the external lighting source, which is finally a kind of noise, because each pixel has its own data, and noise is removed easily comparing with PSD. Although the pixel size of a CCD affects the resolution of the sensor system critically, the problem can be solved if the optical system is adopted to amplify the resolution.

The purpose of this paper is to improve the structure and the performance of the system for 3-dimensional shape measurement using a linear CCD. Until now, most of the 3-D shape profilers using a linear CCD are a computer-based system. It is difficult to move the measurement system based on the computer and the system has the spatial limitation. However, the developed system in this paper has microprocessor and other digital components to make the system measure the displacement of an object without any connection of a computer.

In this system, the different thing from the other previous system is to use AVR microprocessor which calculates the pixel data from a linear CCD sensor and FPGA(Field Programmable Gate Array) technology of Verilog HDL which is to drive the a linear CCD sensor. Especially, most of the systems using a CCD use an A/D converter(Analog to Digital converter) to change the data from the CCD to digital values. On the other hand, in this system a comparator is used to replace the role of the A/D converter. Therefore, where the comparator is adopted, there are just one-bit data line and no address line, and the system consists of FPGA, AVR microprocessor, and the comparator. Furthermore, an ATC(Automatic Threshold Control) algorithm is applied to find the highest pixel data with the actual displacement data. According to the size of the light circle incident on the surface of the CCD, the threshold value to remove the noise and useless data is changed by the operation of AVR microprocessor.

Finally, in this paper, the point is that the structure of the total system is very simple and the amount of data is also decrease, and the ATC algorithm is applied. The character of the developed system is tested through the effect of using the ATC algorithm.

2. LINEAR CCD SENSOR

CCD is an abbreviation of Charge Coupled Device as a sensor of light-current transduction, and generates current proportional to the intensity of incident light on the surface of the CCD. As it is shown at Fig. 1, converting current to voltage is achieved at the end of the vertical transfer line

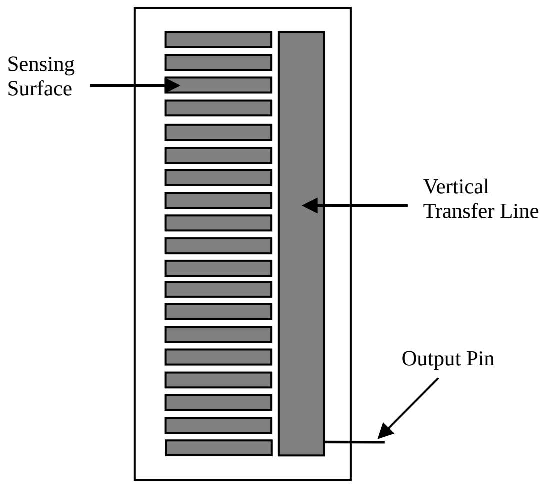

Fig. 1 Structure of the linear CCD sensor

through I-V(Current to Voltage) converter. Thus, the voltage output is dependent on the intensity of the incident light on the surface of the linear CCD. The output voltage is that when there is not any light, it is 4.8V. When the sensor is saturated by a strong light, the output voltage is close to 0V. As the light is more intensive, the output voltage is lower. In other words, the lowest voltage is the highest intensity. Then data from each pixel comes out through the signal output port in series.

Like this, because CCD have one data at each pixel, it is easy to adapt to several algorithm for diverse purposes. Several pulses must be prepared to operate a linear CCD, and a few of components including a comparator and an AVR microcontroller are needed to use the data from output signals for measuring the displacement. This is a basic study for the 3D-shape measurement device, and we will design the driving circuit including pulse generator and address generator by FPGA.

3. OPTICAL TRIANGULATION METHOD AND CONSIDERATION OF ACTUAL POSITION

3.1 The Principle of the Optical Triangulation Method

The principle of optical triangular method is mainly used to measure the displacement of an object when we use a linear CCD or PSD. The method is that if two sides and the angle between them of a triangle are known, the other side of the triangle is decided. This principle is applied to the optical system. In other words, three sides of a triangle are correspondent to the distances between lenses and objects, and angle is equivalent to the angle between above distances. Using this principle, the displacement of an object from sensor will be measured. To achieve the system many components are needed like light source, collimation lens, condensing lens and receiving components such as a linear CCD or PSD. These components should be arranged in the same plane. It means that the area made by the lens among components must be two-dimensional. Fig. 2 shows the principle of the optical triangulation method for displacement measurement from the object.

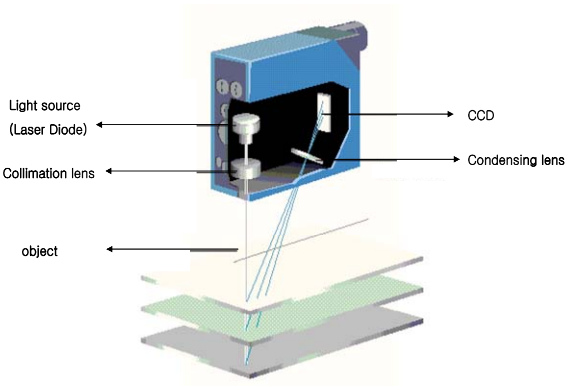

Fig. 2 The principle of optical triangulation method to measure the displacement from the object

When the light source is incident on the surface of object, the light point is made and it generates diffused reflection. Condensing lens collects the reflected light from the object, and the dense light makes the image point on CCD. If the object moves along z-axis, the image point on the surface of CCD moves along the axis correspondently. The line by the movement of light point is called objective trajectory and that by movement of image point is called image trajectory. Triangulation system has a good price vs. performance ratio, in addition, it is highly accurate and can measure distance up to some meters. Geometrically it can be designed to have any range from a very short distance signal to noise ratio. The accuracy of this system decreases with distance.

3.2 Problems of the Optical Triangulation System

The main problems of the triangulation system are the nonlinearity from the differences of flying distances at the points below and over the stand off distance(D) as shown at the Fig. 3.

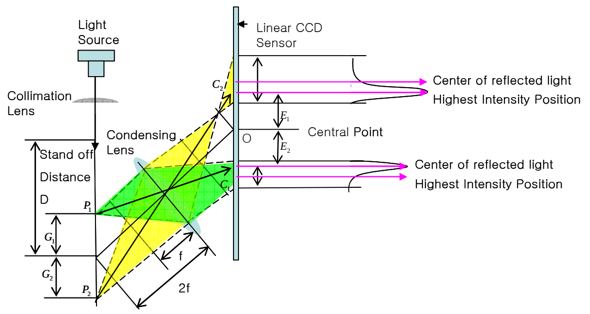

Fig. 3 The different image lines by optical triangulation

In addition, the system have the problem by the possibility of occlusion and measures on specular surfaces that can blind the sensor or give rise to wrong measures due to multiple reflections. Fig. 3 shows the different image lines. In the Fig. 3, P1 is the point over the stand off distance and P2 is the point below the stand off distance. In addition, C1 is image area by the reflection light at P1, and C2 is image area by the reflection light at P2.

It penetrates the focal point, when light beam is parallel to the axis of condensing lens. In addition, light beam is parallel after it penetrates the focal point at the front side of condensing lens. As shown at the Fig. 3, the image line by lighting point C1 is wider than that by lighting point C2. The nonlinearity is generated by the different intensity according to each point on CCD surface. Although distances of G1 and G2 are the same, E1 and E2 have different distances in experiment despite their being the same theoretically. It means that the wider area at E2 generates more error than at E1. Namely, the symmetry at E2 disappears much more ratio than at E1. It generates more nonlinearity at negative direction from the stand off distance than at positive direction.

In this optical triangulation experiment, we did experiment using the linear CCD ILD1400 made by the company, MICRO EPSLONE. The error rate of negative direction from the stand off distance D is higher than that of positive direction as shown Fig. 2. The full range of Z-axis is ±6mm, and output voltage level is ±10V.

3.3 Consideration of Actual Position for the Improvement of Nonlinearity

The highest intensity point is at the distance of E1 and E2 from the central line of a linear CCD sensor. Therefore, if we know the exact point where intensity is highest, the displacement E2 is decided and it result in measuring G2. At the highest point among C1, the G1 is decided. As written at first, CCD has data at each pixel. Therefore, we can check the pixel having highest data using microprocessor such as DSP, AVR at memory storing pixel data. In this paper, we performed the experiment for the reason generating nonlinearity of a linear CCD using optical triangulation. Although object trajectory is linear with image trajectory, image line is longer and dispersion of light get more increasing when object is farer from the stand off distance. Accordingly, the symmetry of intensity function decreases, and that generate nonlinearity of a linear CCD. If the exact highest intensity point is known, the distance will be measured accurately comparatively.

However, the reflected light is very different according to the roughness of the object to try to measure. Therefore, we must consider which position is the real position of the object. As followings, the reflected light is divided to several styles.

First of all Figs. 4~6 styles, Fig. 4 shows that the actual position on the reflected light by the object having the smooth surface. The light is incident on the part from S1 to E1. The highest intensity pixel has objection position information since the incident surface is symmetric.

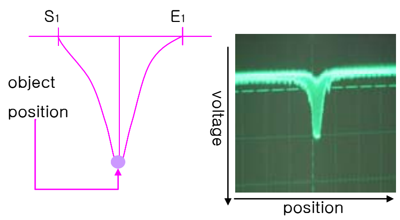

Fig. 4 The actual position on the reflected light by the object having smooth surface

The second style, Fig. 5 is the case of the actual position on the reflected light by the object having the rough surface.

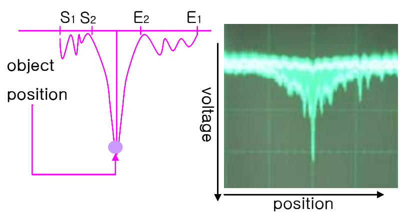

Fig. 5 The actual position on the reflected light by the object having rough surface

The part from S1 to S2 and from E1 to E2 causes from rough surface. The system detects the different pixel dependent on the threshold voltage and the highest intensity pixel has objection position information because the main incident surface is symmetry.

The last style in the below Fig. 6 is the actual position on the reflected light of very rough surface of the object.

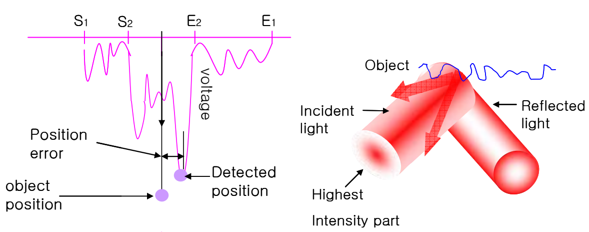

Fig. 6 The actual position on the reflected light by the object having very rough surface

The part from S1 to S2 and from E1 to E2 also causes from rough surfaces and the system detects the different pixel dependent on the threshold voltage. The highest intensity part of incident light is on the center, but the highest intensity part of reflected light is not on the center, and it is outer part. Thus, there are some position error between object position and detected position.

4. SIGNAL PROCESSING FOR DETECTING THE REAL DISPLACEMENT

4.1 A Linear CCD Circuit Design

The linear CCD, ILX555K made by SONY Corporation has three-color pixel lines, but we did not have to use all the three lines. We used the only red output pixel line because the red laser diode is used as the light source. When the only pixel line is used, we can get the more sensitive signal from the used color pixels than other two unused color pixel lines.

Several pulses from FPGA chip are used to drive the linear CCD, but its current maybe is small to operate as the driving pulse. Thus, that is the reason why the inverters are inserted between FPGA and the linear CCD. After that, pulses play their roles exactly. The inverter 74HC04 made by Philips is used. The output signal from the linear CCD is very rough to use itself, so it needs to amplify or decrease. In the previous system the output signal enter A/D converter as the next component and that is why the range of the output signal must be adjusted to the accessible range of A/D converter. However, in this system A/D converter is not used, and it does not need to change the output voltage level. The Fig. 7 below shows the circuit to drive the linear CCD.

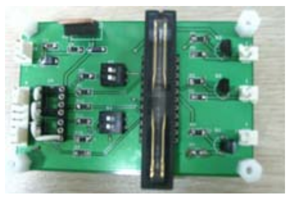

Fig. 7 The completed driving circuit of the linear CCD

4.2 Digitalizing by using a Comparator

A comparator is to digitalize the output signal from the linear CCD in order to calculate the displacement in AVR microprocessor using the data. Generally, the A/D converter is used to digitalize and its resolution is good as high as possible, and then the amount of data to process is increased. However, in using the linear CCD, the resolution is not as critical as other devices like PSD. When optical signal at each pixel of the linear CCD comes out, we want to know just whether the light is incident on the pixel or not, it means that it is not important how intense the light is. That is the reason why the comparator is used instead of the A/D converter.

Compared to applying A/D converter, when the comparator is used as the component to digitalize the data from the linear CCD, the amount of data is decreased about 1/8. When the 8bit A/D converter is used, the amount of data is 86400bit to process a line of the linear CCD, but 10800bit is just needed in case that the comparator is used. Actually, the comparator is not digital chip but analog chip, and when the chip gets the higher input voltage than the reference voltage, it sends the positive supply voltage. In addition, when the comparator gets the lower input voltage, the output voltage is the same as that of the negative supply voltage. Like this, the comparator is just a comparing device. Although it was an analog chip, if the negative and positive supply voltage would be the same as the voltage level of digital signal, it could be the digital chip. In this paper, the negative supply voltage is the ground level and the positive voltage is 5V, which is perceived as the high state in the digital system. Another advantage is that the sampling frequency is not used any more; on the other side, it is needed to use the A/D converter. Because the chip works the continuous comparing, not according to the input clock, it means that the comparator operates asynchronously. The important thing is the slew rate, which is the possible voltage change at the 1 second. As high as this value is, it can work well at the application using the high frequency CCD. The used comparator in this paper is the LM311 chip made by NATIONAL SEMICONDUCTOR.

4.3 Automatic Threshold Control Algorithm

An automatic threshold control algorithm is applied to find the highest pixel data that has the real displacement information. According to the size of the spot size incident on the surface of the CCD, the threshold value to remove the noise and useless data is changed by the operation of AVR microprocessor. When the size of the light incident on the surface on the linear CCD is large, it means that the incident light is dispersed and the shape of the circle can be distorted easily. If so, noise is increased and the data of the displacement is not exact. As shown in the Fig. 8, we assume that the sampled size is larger than the current threshold voltage of the upper limited spot size. If the threshold value becomes lower to the revised threshold voltage direction of increasing the output voltage, the size gets smaller and noise is less than previous.

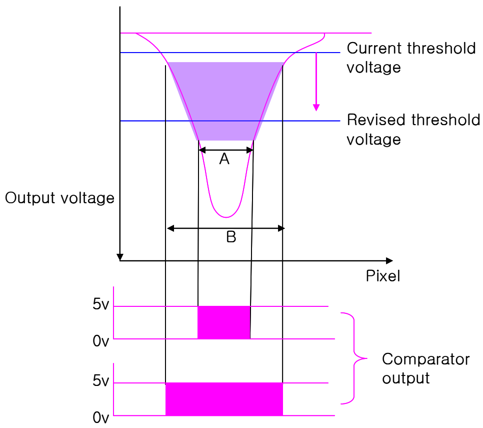

Fig. 8 Automatic threshold control algorithm in case of the large spot size

In the other way, when the size of light incident on the surface of the linear CCD is small, it means that the incident light is very rare or the threshold is too low to detect the spot size. If so, a wrong data can be detected, and the data of the displacement is not exact. In case of that, if the threshold value became higher, the size gets larger and noise is less than previous. Thus, threshold voltage changes according to the size of the incident part on the linear CCD.

4.4 The Method for Finding the Highest Intensity Position

To control all of the signal interfacing with other components, microprocessor is needed and AVR is used as playing that kind of the role. Among many AVR series, AVR Atmega 128 model which is 8bit microprocessor having the basic clock 16 MHz is used.

All of components on this system are connected to AVR microprocessor. First, it exchanges signals with FPGA chip and it control to operate FPGA. The number of pixel per line is 10800 and the output data is 10800 bit per line. When all of data in a line comes out, AVR microprocessor gets the signal continuously and works the mathematical operation. Then, AVR microprocessor gets the data changed to digital data. After AVR microprocessor gets the data from the comparator, it changes the data to displacement information using the algorithm to find out the point where the light is incident, and automatic threshold algorithm. The calculated displacement information is sent to the device; character LCD using RS-232 serial communication protocol. Then, users can know the displacement of an object. This system repeats the one cycle operation about 25 times a second, which means the frequency of the system is 25Hz.

For the detailed method to find the highest intensity position, when the light is incident on the surface of the linear CCD, the intensity of the light can be expressed as Gaussian function. When we have only to know the two points, the starting point and the ending point, if there would not be any distortion, we can know the center point, which means the displacement of the purposed object. As shown in the Fig. 9, when a new line of the linear CCD starts to send the analog signal, AVR microprocessor starts to count.

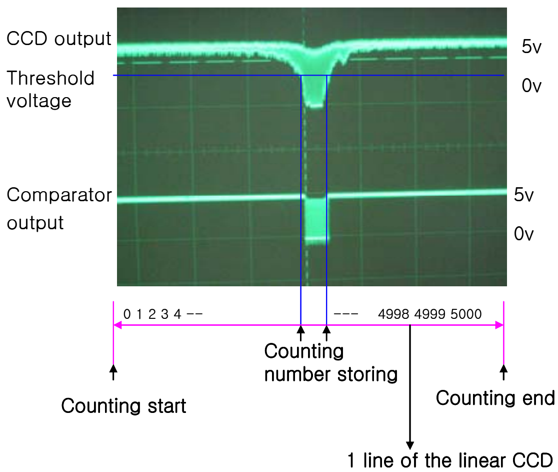

Fig. 9 The counting method for finding the highest intensity position

Then when the comparator output is falling, AVR microprocessor stores the counting number at the edge. At last, AVR microprocessor stores the counting number at the last edge. Using the two stored number, the size of incident part can be calculated. Therefore, the center of two numbers is the highest position. When finding the center point, I used the threshold value, which expresses that the light is incident surely and the value is changeable according to the external environment like fluorescent lights, sunlight and some objects to increase the surrounding temperature.

4.5 Extra Considerable Signal Processing Parts

On processing the signal in this system, there are some points to consider importantly such as voltage level shifting, removing noise and dark current on the linear CCD etc. First, the laser diode is to be on and off repeatedly at the frequency 25Hz which is the same frequency as the system not to continue to turn on. Because it makes the life time of the laser diode longer and has the noise current less.

The input and output voltage of FPGA is 3.3V level, but such component as AVR microprocessor is 5V level. It does not matter when signal enter other components except FPGA. However, when some signal enter FPGA, because FPGA is just accessible within 3.3V. 5V must be shifted to 3.3V. In order to do that level transceiver chip, 74LCX245 made by FAIRCHILD are used.

In this system, the red laser diode is used as the light source. When the focus of the laser diode is incident on the pixel array of the linear CCD exactly, although the light is weak, it is easily saturated on all of the pixels. To avoid the saturation, the thin dark film is covered on the surface of the linear CCD. In addition, it blocks fluorescent light and daylight and so on. If not, although the circuit to drop the analog output voltage is used, it is useless. Because the output voltage of the sensor is already saturated, and the saturation voltage has just changed, when the shifting circuit is used. The reason why the saturation happens so easily is that the linear CCD used is very sensitive and the current overflows along all pixels, and the light is reflected very strongly, which means that the light spot on a pixel affects other pixels although they are away from the pixel. The used laser diode has red color and the wavelength 650nm. In addition, there is the optical filter at the front side of the linear CCD, which is to remove the white noise, fluorescent light and sunlight.

5. EXPERIMENT RESULT

5.1 Z-Axis Position Signal

All of the experimental results discussed the differences at the case of applying the automatic threshold and not applying about control Z-axis signal, spot, and nonlinearity. In addition, the position measurement was performed at the gap size, 500um and the measurement range, 10mm. At the below Figs. 10~11, they showed that linearity was improved after applying the automatic threshold control algorithm.

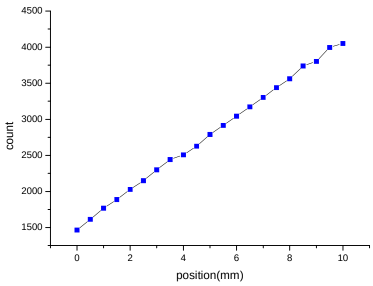

Fig. 10 Z-axis position signal at each 500um

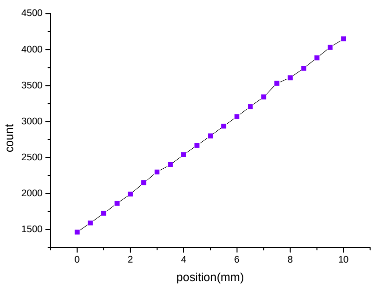

Fig. 11 Z-axis position signal at each 500um after the ATC

5.2 The Size of Incident Surface on the Linear CCD

At the below Fig. 12, before applying the automatic threshold control algorithm, there were many sizes of incident surface over 1mm. It means that the signal is not accurate and noisy.

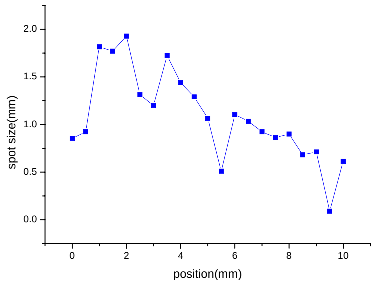

Fig. 12 The size of incident surface at each 500um

However, most of the sizes of incident surfaces were smaller than 1mm after applying the automatic threshold control algorithm as shown in the Fig. 13.

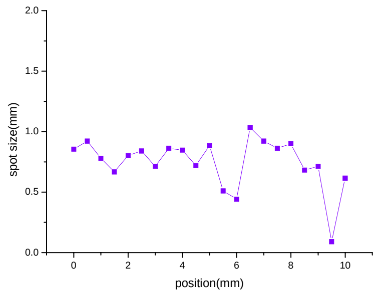

Fig. 13 The size of incident surface at each 500um after applying the ATC

We can be sure that the automatic threshold algorithm is effective to improve the performance of the linear CCD for shape measurement.

5.3 Nonlinearity of Position Signal

The nonlinearity was about from -3.2% to 2% and it was very high as the displacement sensor in the Fig. 14.

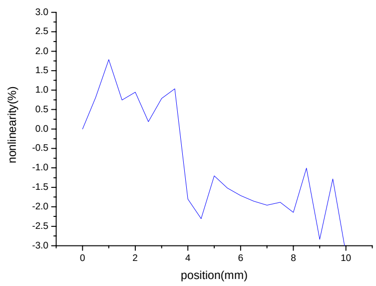

Fig. 14 The nonlinearity at each 500um

However, after applying the automatic threshold control algorithm as shown in the below Fig. 15, the nonlinearity was between -1% and 1%. Of course, this was not so good, but using the proposed new algorithm and the comparator instead of A/D converter the performance of the system was improved.

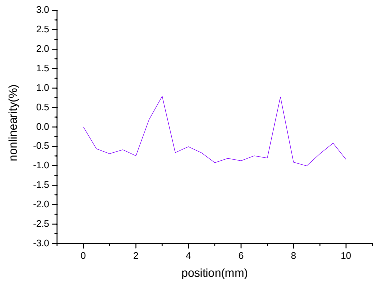

Fig. 15 The nonlinearity at each 500um after applying the ATC

6. CONCLUSION

In this paper, the ILX555 made in SONY Corporation was used for the study on the performance improvement for displacement measurement system using the linear CCD. In result, using the comparator instead of the A/D converter the structure of the total system became very simple and the amount of data was also decreased, and the automatic threshold control algorithm was applied. In the each experimental result, we could see the performance of the system was improved comparing with the system, which did not adopt the ATC (Automatic Threshold Control) algorithm. Namely, the nonlinearity was decreased and the accuracy was increased. The resolution was 1/3300 of the full measurement range. To improve the displacement measurement system using a linear CCD, the optical noise was removed by adopting the optical filter, which passed the light having the wavelength sensitive to the linear CCD and blocked the light having the wavelength out of the band-pass. In addition, as the experimental result of the nonlinearity of the position signal, if other parts like signal processing circuit or time count become better than previous, the system will be improved very much. In addition, if possible, it is better that most of the algorithm and the mathematical operation is performed in a one chip to make the electrical noise less. With the above ways, when the algorithm to find the highest pixel is applied, the system will be more accurate and can measure the more exact displacement of an object.

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