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The Basic Research for the New Compass System Using Latest MEMS

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ABSTRACT: This paper demonstrates basic research for a new compass system using latest MEMS (Micro Electro Mechanical Systems) sensors for small vessels. In 2007, MEMS Electro-statically Gyro (ESG) was introduced by TOKYO KEIKI which is a Japanese company. This sensor accuracy has dramatically improved compared to vibration types. For example, instability has been improved 10 times more than the vibration types. The reproducibility was tested and maximum difference was 0.55 [deg/sec] in the field test. The MEMS-ESG could detect the relative angles as accurate as GPS compass in short term use. Even though sensor accuracy has been improved, an improvement of another 10 times is needed to detect the earth's turn rate. Because of this a second system is required for a complete compass system. A celestial navigation system is one of the possibilities to complement this. Traditionally the sextant has been used for measuring the altitude, but it has some human errors and difficult to measure continuously. Therefore, it might be useful to get sun altitude and direction automatically. In this thesis, the sun altitude and direction detecting system using camera devices are studied. Using 350×288 resolution camera and a radio-controlled clock, the sun movement was detected 5'14" per pixels and 2'16". per pixels for the altitude and direction respectively. Although this is a basic research for an integrated system, the data should have an enormous affect upon future research.

1 INTRODUCTION

1.1 *Background of the Research*

Small vessels have a choice of Gyro compass, magnetic compass or GPS compass. They are also using the GPS for calculating positions.

Even though GPS is very accurate, small and low cost, it needs signals from satellites. Because GPS is worked by external signals from satellites, several weak points have been discussed, for example, jamming, maintenance cost, electromagnetic wave by the sun and etc. Therefore for the purposes of this research we studied an autonomous system without using GPS.

The Inertial Navigation System is an autonomous and overcome the problems that are caused GPS. In the recent technological advancements modern inertial systems have removed most of the mechanical complexity of platform systems by having the sensors attached rigidly to the body of the host vehicle. It is called the strapdown inertial navigation system. But to maintain its accuracy, it still needs very accurate systems such as the ring laser gyro (RLG), the fiber optic gyro (FOG) or more accurate gyro such as the electro-statically suspended gyroscope (ESG) and also very complex systems. Those systems are expensive and uneconomical for small vessels but new type of MEMS sensors should provide a possible solution to this problem.

In this research, the basic researches were carried out for the stated goal that is developing a small and low cost autonomous system which is affordable for small vessels.

1.2 *The Integrated Compass System*

MEMS-ESG is able to detect relative angles which discussed in this paper. For the compass system, absolute angles are necessary. Therefore integrated system was being looked at. The considering system is using INS with MEMS-ESG and sun direction and altitude detecting system using camera image. The system diagram is shown in Figure1.

INS using MEMS-ESG is able to navigate for only 2 minutes or less, Gen F. & Shogo H., 2008. One of the problems is cumulative errors. There for the camera system update time should be within that time.

In this thesis, the MEMS-ESG is introduced in the second paragraph and then the camera system is introduced in 3rd paragraph as basic research for the integrated compass system.

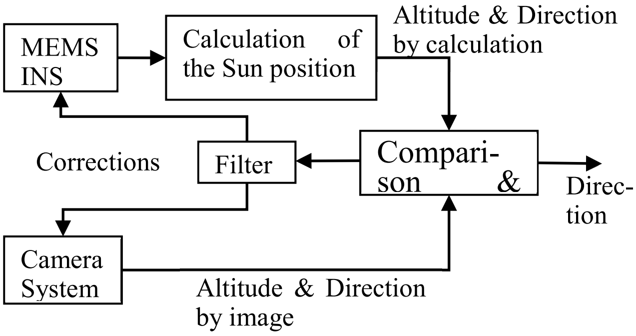


Figure 1 Integrated Compass System

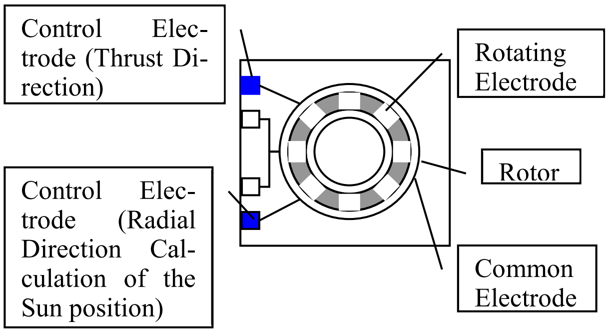
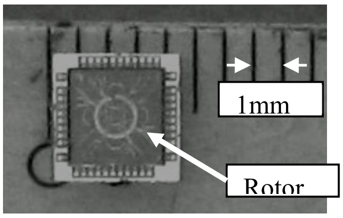


Figure 2 MEMS-ESG Sensor Structure



Picture 1 MEMS-ESG Sensor Package

2 MEMS ELECTRO SUSPENDED GYRO SENSOR

2.1 *The basic research of MEMS-ESG*

The ESG is introduced during the 1950s in the United States. The ESG is very accurate and it has achieved drifts of the order of 0.0001[deg/h] and navigation accuracies of the order of 0.1 nautical miles per hour, David Titterton and John Weston. 2004. Unfortunately, despite being very simple concept, the design is complex and the gyroscope is large and expensive.

The MEMS-ESG was introduced by a Japanese company in July 2007. Although the accuracy is not the same as the previous ESG, its accuracy is greatly improved as MEMS gyro sensors. Additionally it is lower price than the previous ESG.

The MEMS-ESG is measuring the turn rate using the turning sensor rotor which is suspended by electrostatic power. When the turn rate is applied to the rotor, a slight tilt angle is occurring between sensor rotor and sensor case. A feedback torque is applied in order to return the rotor to the normal position. This feedback torque is proportional to turn rate, so the sensor can detect the turn rate. In addition, the sensor detects the 3-dimension accelerations by the torque which is applied for maintaining the sensor rotor in the center of the case.

The MEMS-ESG sensor structure has 3 layers that are glass, silicon and glass. The sensor structure image is shown in Figure2. The sensor size details are shown in Table1. Picture 1 shows the sensor package. The package is 4.3[mm] squared and 1[mm] thickness, Shigeru Nakamura. 2008.

Table 1 Rotor information

Rotor diameter	1.5[mm]
Thickness	50[μm]
Top and bottom gap	3[μm]
Radial dimension gap	2.5[μm]

2.2 *Rate Output*

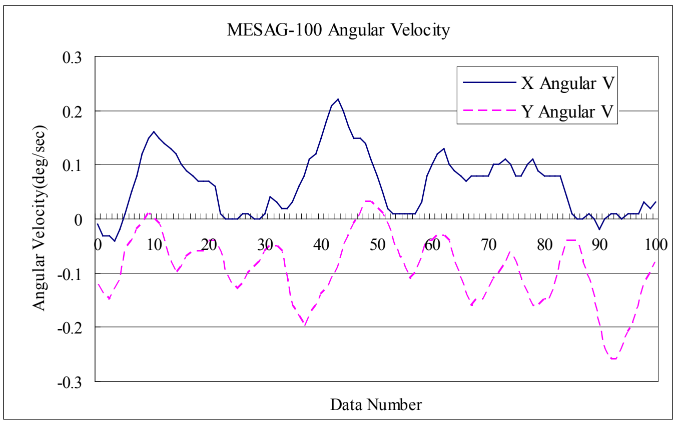


Figure 3 X and Y axes angular velocity output by MEMS-ESG

Figure 3 shows 100 data of the angular velocity output about X and Y axes by MEMS-ESG. The data was collected in the laboratory in stable conditions. The vibration type gyro sensor's output was collected at the same time. The comparison of the MEMS-ESG with vibration type is shown in Fig 4.

In this case, the average output of rate sensor by the MEMS-ESG and a vibration gyro are 2.844×10^{-17}[deg/sec] and 0.131[deg/sec] respectively. Instabilities are 0.260[deg/sec] for MEMS-ESG and 3.125[deg/sec] for a vibration gyro.

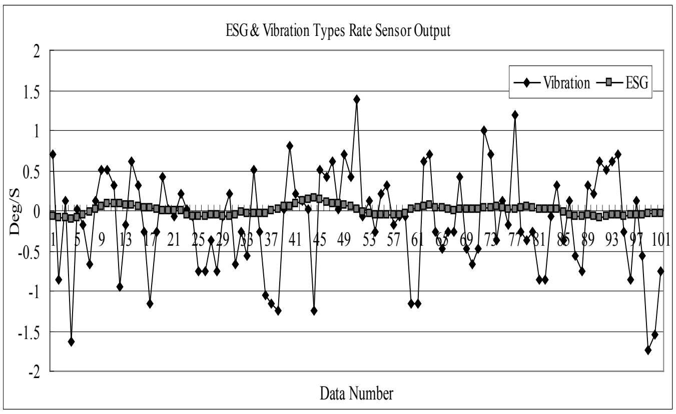


Figure 4 Comparing Vibration with ESG type

2.3 *Reproducibility Test*

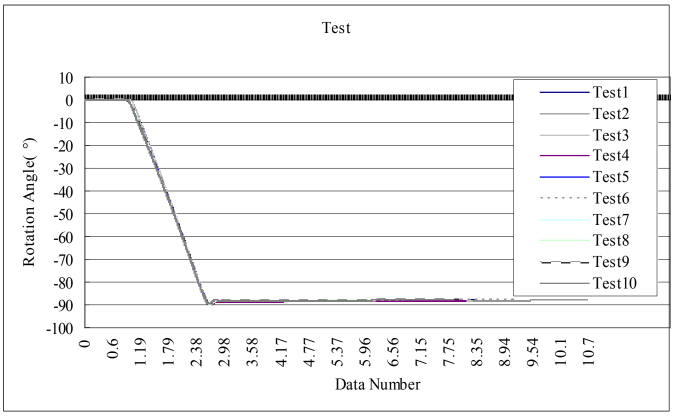


Figure 5 Ten times relative angle reproducibility test

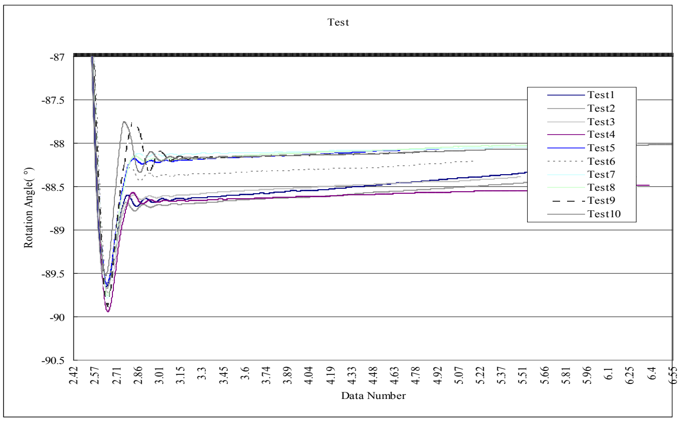


Figure 6 The enlarged figure of vibration point

Ten times relative angle reproducibility test was carried out. The sensor was rotated about 90 degrees by motor and stopped mechanically by using a relay switch. Figure 5 shows the test result. The data shows good reproducibility in short term use. The biggest difference of this data was 0.550 [deg/s] around the sensor stopped point which is shown in Figure 6. It was considered that that difference was caused by the small vibration caused by the reaction of the mechanical stop.

2.4 *Acceleration Output*

It is shown the X-axis acceleration output in the stable condition in Figure 7. The compared with the vibration type acceleration sensor was shown in Figure 8. In this figure, the average output of acceleration sensor output by MEMS-ESG and vibration are -1.215×10^{-18}[G/sec] and -0.002[G/sec] respectively. Instabilities are 0.002[deg/sec] for MEMS-ESG acceleration sensor and 0.053[G/sec] for vibration acceleration sensor.

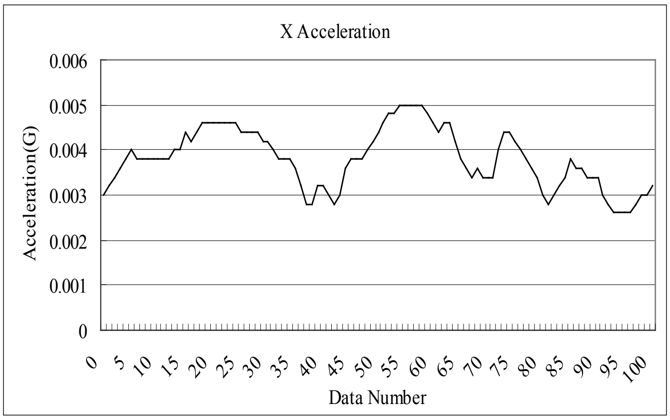


Figure 7 X-axis acceleration output

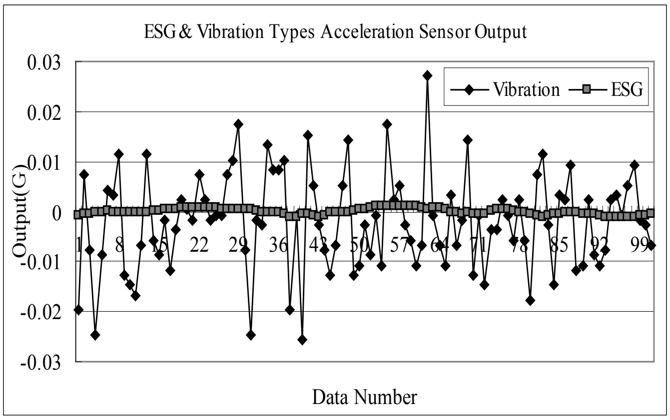
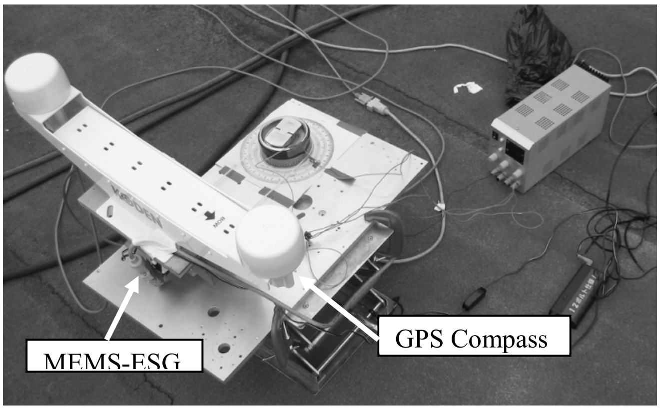


Figure 8 Comparing Vibration with ESG type

2.5 *Comparing with GPS compass*



Picture 2 GPS compass and MEMS-ESG for the comparing test

The comparing test was held using GPS compass. The GPS compass was fixed on the MEMS-ESG and both equipments are rotated simultaneously by DC motor. The equipment was shown in Picture 2.

Figure 6 shows the relative angle by the MEMS-ESG and GPS compass output. The MEMS-ESG is able to measure the turn rate as accurate as the GPS compass in short time use. The GPS compass data has some data blanks since the GPS compass could not get the signal from the GPS satellite, whereas MEMS gyro is able to get the data continuously. This result might suggest that the GPS/INS is very useful in some areas.

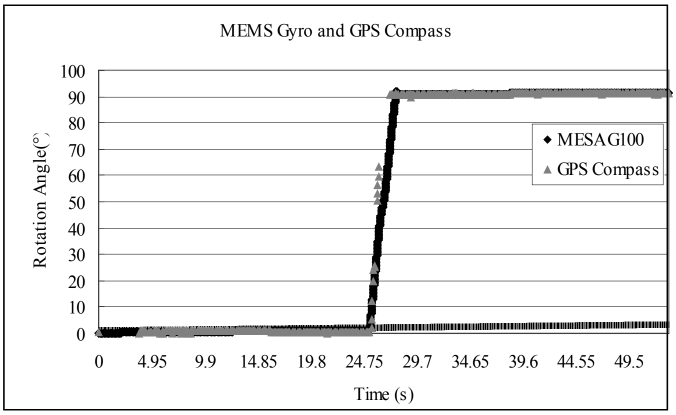


Figure 6 MEMS Gyro and GPS compass Output comparison

2.6 *Existing problems with MEMS-ESG*

The MEMS accuracy improvement was discussed in 2.2 and 2.4 by comparing the ESG type sensor and the vibration type. ESG type is very useful concerning its accuracy but it requires some techniques to provide shock and vibration protection. The vibration type gyro sensor which discussed in this paper has 2000 g-powered shock survivability, but ESG type has got only ±15[G] at 1[kHz]. For example, when we carried out field test by the car, the sensor was sometimes stopped because of the light shock by the brake. This problem is reported not only MEMS-ESG but also the normal type of ESG gyro as well. Before considering using the MEMS-ESG on a ship, this problem must be solved.

Moreover, the sensor box surface temperature is increased as shown in Figure 10. The test was carried out in the laboratory where the temperature was 27.5[°C]. The sensor box surface temperature was increasing and reached 44.8[°C] in 110 minutes. This was caused mainly by FPGA (Field Programmable Gate Array) in the sensor box. This is not directly caused by sensor itself but concerning affordable sensor temperature which is from -20[°C] to 55[°C], it would be necessary to resolve this problem in some environments.

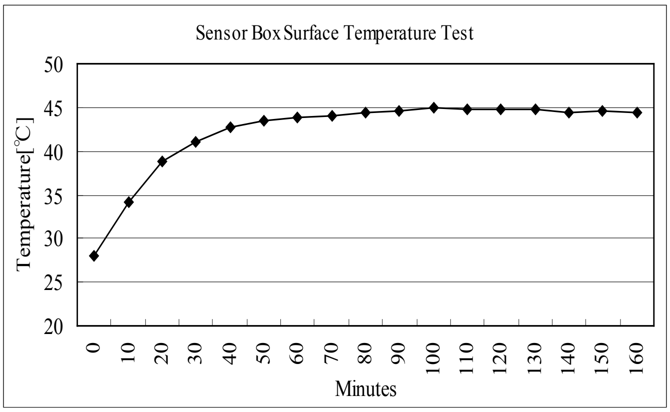


Figure 7 Sensor Box Surface Temperature Test

3 SUN DIRECTION AND ALTITUDE DETECTING SYSTEM USING CAMERA IMAGE

3.1 *The general outline of the system*

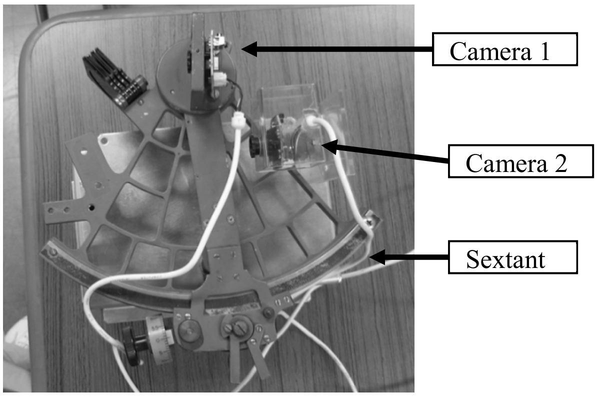
MEMS-ESG is capable of detecting relative angles. But it also needs to know the absolute angles for the compass system. Therefore second system is needed.

Gyro compass has normally been used for that. But it is expensive and too big for small vessels. The magnetic compass, the celestial navigation and the terrestrial navigation are traditionally used on the ship. The magnetic compass is one of practical solutions but it has got the problem of deviation. The celestial navigation is also powerful tool but it needs to detect the altitude using a sextant by hand. This would cause the human factor errors. It is also difficult to observe continuously. But considering the celestial navigation is still using on some ships for a complement of GPS, it is still useful if it is automated. There is available radio sextant as an automated system for this but the equipment cost is too expensive. Therefore the web camera was considered to measure the sun altitudes and directions. According to recent development of imaging device, they are getting cheaper and higher resolutions. There is the system using CCD cameras, Fabio C. & Erik K., 1995. But high resolution CCD cameras are still expensive.

3.2 *Direction and altitude calculation*

The system needs to calculate the sun position. It needs very complicated calculation to get the real sun position. Therefore the calculations have been completed using a polynomial approximation of ephemerides, which was invented by Hydrographic Office of Japan, Japan Coast Guard. 2008. It would be considered that there are slight differences between a polynomial approximation and Nautical Almanac. If using high resolution cameras, those difference are should be considered.

3.3 *Camera device*



Picture 3 Camera Device used the evaluation

There is the system using fisheye lens, Matthew C. D., David W. & Daniel V., 2005. The fisheye lens is very useful because it could detect the sun only one camera without any mechanical moving devices. But there are few fisheye lenses for web cameras. They also need many calibration works.

Therefore two cameras are used in this system. They are 352×288 pixels web cameras and put on the sextant for evaluation as shown in Picture 3. Camera1 expected to take sun image and camera 2 is expected to take horizon. Both cameras are connected with PC by using USB cables.

3.4 *The result*

The calculation for the altitude and direction is produced by Kenji Hasegawa, 1994. The result of sun altitude by calculation and camera image for 22 minuets are shown in Figure 8. Figure 9 shows 500 data in Figure 8. The sampling time is 0.5[sec]. The time was given by a radio-controlled watch. There are two flutters which show in Figure 9 around at 14:53:3 and 14:54:40. This would be caused by the interlace scan.

The maximum difference and standard deviation with calculated data and camera image data are 0.0932 degrees and 0.0246 degrees respectively. The calculated sun altitude is moving uniformly, as you would see in Figure 9. But the altitude by camera image is moving like steps. This is caused by the camera resolution. In this case, it is detected 0.0872 [degree/pixel], which is equivalent to 5’14”.

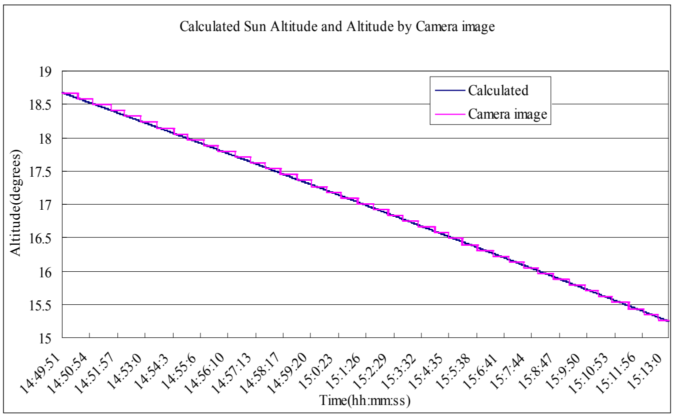


Figure 8 Calculated Sun Altitude and Altitude by Camera Image

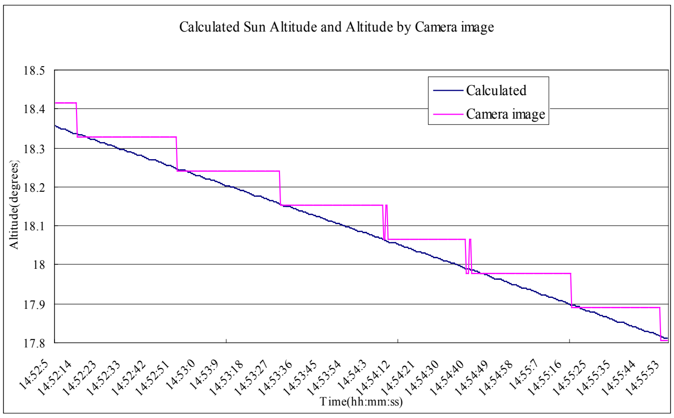


Figure 9 The 500 data in Figure 8

The results of sun direction by calculation and camera image are shown in Figure 10. Figure 11 shows 500 data in Figure 10. A sampling time is 0.5[sec]. The time was given by a radio-controlled watch.

The maximum difference and standard deviation between calculated data and camera image data are 0.0647 degrees and 0.0054 degrees respectively. The resolution is detected 0.0378 [degree/pixel], which is equivalent to 2’16”.

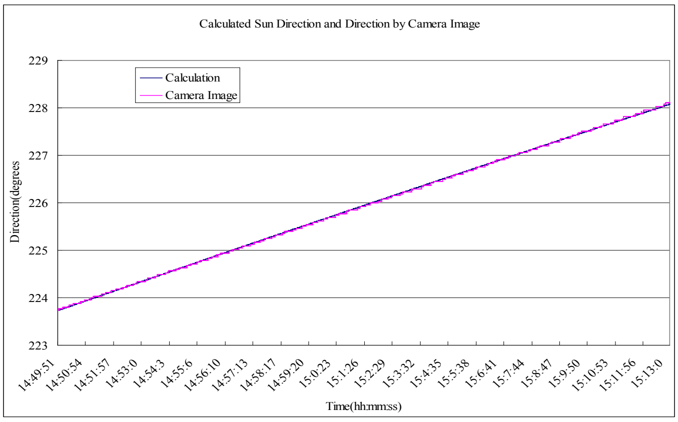


Figure 10 Calculated Sun Direction and Direction by Camera Image

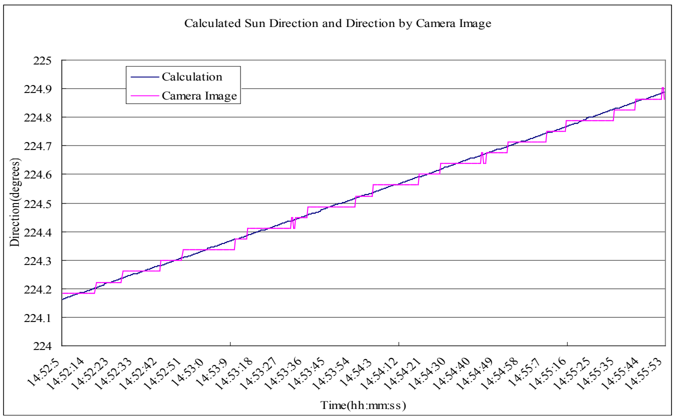


Figure 11 The 500 data in Figure 10

The reason of resolution difference between Altitude and Direction was caused by the initial camera attitude error. Further more, the camera focus error is considered as the error term.

4 FUTURE WORKS

A position data is demanded for the calculation of sun altitude and direction. The MEMS INS is possible way to calculate the position. The MEMS INS is demanded to keep its accuracy while the camera system is updating the sun position and altitude. Using the camera system in section 3, more than 2 minuets updating time is demanded. Therefore the INS using MEMS-ESG needs more accuracy, Gen F. & Shogo H, 2008. Many books are published for the INS calculation such as David Titterton and John Weston. 2004. But those calculations are considering more accurate sensors. Now, the INS program for the MEMS-ESG is under researching.

There is accuracy difference between the X-axis and Y-axis. This difference might be caused by the CMOS sensor in the camera and also initial alignment errors. The studies have been undertaking about it. In addition to that, the research using higher resolution web camera is also undertaking.

5 CONCLUSION

In this paper, the new type of MEMS sensor, MEMS-ESG, and the sun altitude and direction detecting system were explained as basic research for the new compass system using latest MEMS.

An accuracy of MEMS-ESG has much improved comparing previous vibration type of MEMS sensors. The sensor's reproducibility was explained. Furthermore, the relative angle accuracy was shown comparing with GPS compass. The problem of MEMS-ESG is explained in 2.5. Especially, some countermeasures are needed for the shock survivability on the ship. Although there are still some problems with MEMS-ESG, it has got much potential. The vibration type sensors would be difficult to increase their accuracy because of their structures. However, ESG type has different structures and easier to increase its accuracy. For example, inertial momentum is proportional to the square of rotor's diameter and also rotor's rotation rate. To consider those and the fact that the company has already made successfully the bigger diameter rotor sensor, MEMS-ESG accuracy would be increased in the future.

In 3rd paragraph, the sun altitude and direction detecting system using camera image was explained. Using 352×288 resolution web camera, the accuracy achieved 0.0872 [degree/pixel] for the altitude and 0.0378 [degree/pixel] for the directions.

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