A NEW SYSTEM OF SURFACE MEASUREMENT

N.Kochi,H.Ohtani,S.Nakamura,T.Utiyama,M.Yamada,M.Chida,T.Noma,T.Ito,H.Aoki
Topcon Corporation
75-1,Hasunuma-Cho,Itabashi-ku,Tokyo,174 Japan

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ABSTRACT:

The objective of our research is to create a practical "new system of surface measurement". It is the system to measure the body surface irregularity and curve by means of highly accurate 3D measurement through photogrammetry.
Lately, the exterior characteristics of a train body, for example, are increasingly diversified in its form, color, length etc. For example, often times, its surface is plain without design, or sandy with sandblasting or simply lustrous, or three dimensionally deep with curve, all of which characteristics make it so much more difficult to measure by automatic stereo-matching. Besides, when an object to be measured is large, not only more accurate but also faster measurement will be necessary.
The system we have developed consists of an image acquiring part of two high-resolution CCD cameras (16.77 million pixels) and an image analyzing part of stereo-image-workstation PI-1000. And its measurement is done with the automatic stereo-matching mode based on "the coarse-to-fine correlation". Through the analysis of our PI-1000 we can obtain the image with stereo-contour-lines, the perspective view as well as the cross section of an object. Besides, the data obtained by our PI-1000 can be output in multi-applicable format (DXF) of CAD, and thus can be used for many purposes.
Therefore, as a preliminary experiment we executed the stereo-matching on various simulated surfaces and measured the accuracy of our system. And then we proceeded to test it actually on the flat surface of a real train of stainless steel as well as on the nose (length 1m, width 3m, depth 1m) of a bullet train of Japan Railway for 3D measurement.
This paper will explain the general outline of our system, the data of the above tests and their inputting into CAD systems as an example of the CAD application.

1.INTRODUCTION

Since weight alleviation is now sought as far as possible in the construction of all vehicles (in our case we test on the railroad vehicle), their exterior surface board tends to be thinner and interior frame, to be more slender. Therefore, it is becoming increasingly difficult to maintain the surface flatness. Especially in the stainless steel body, it is almost impossible to take out the welding distortion. At present the measurement of the flatness of body surface and the measurement of the nose curve are done by a steel tape hand work, which, of course, is not so accurate and can not any way be called modern as it is not able to assure the same exact result in repeated measurement and effective data controlling.

It is, therefore, imperative to develop a new device which allows us to measure the flatness of body surface highly accurately to facilitate the quality control and the examination of the aging.

The system we have developed consists of the image-acquiring part and analyzing part.

Our high resolution CCD camera has 16.77 million pixels and is made such a way that while the focal length is changeable, its principal point does not fluctuate. And for camera lens, we have developed a special and low-cost lens whose distortion curve does not change even with the change of focal length. Our high resolution CCD camera, therefore, requires the calibration only once.

For camera-calibration we use "the Self-calibrating bundle adjustment software", which we developed. We have also developed, however, a new software to detect automatically targets placed on 3D testified designed for calibration.

In order, therefore, to confirm and verify the high accuracy of our measurement devices we made the following two kinds of experiment. First, for exterior surface flatness measurement we tested on the simulated sandy and lustrous surfaces and then applied it on the actual surface of a stainless train body. Second, for curve surface measurement we tested on the simulated curve surfaces and then applied our method on the actual nose of a bullet train.

Thus, in this presentation we will first present the general outline of our system, and then its experimental results, followed by the examples of the data-inputting into CAD systems.

2. OVERVIEW OF THE SYSTEM

The surface measurement system we have developed is an analytical stereoplotting system for digital image. As shown in Fig.1,2 the system consists of an image-acquiring part and image-analyzing part.

The image data that are obtained by taking a pair of left and right stereo images are stored in the separate optical or hard disks for respective side and then transferred into a stereo-image workstation (PI-1000) and analyzed therein.

2.1 Image-Acquisition

The image-acquiring part is composed of two high-resolution CCD cameras, a pattern texture projector and base-bar. The CCD cameras and projector are placed on a base-bar and can be easily moved about in a unit to acquire images on the surface of a vehicle's body.

Our high resolution CCD camera has 4096 × 4096 pixels and is made such a way that even if the focal length is changed, its principal point does not fluctuate.

And this time, for camera lens we have developed a special and low-cost lens whose focal length is 29mm, maximum aperture is 4, and the view angle is 68° with its peripheral distortion contained within the range of 0.05%. With the former metric camera, we were obliged to carry out the camera-calibration each time the focal length had to be changed or the lens had to be replaced. Our new high resolution CCD camera, however, requires the calibration only once, even though the focal length changes with different objects .

The Fig.3 shows the fluctuation of the principal point with the change of the focal point. Here the fluctuation range is contained in less than one pixel (CCD pixel size : 7μm square).

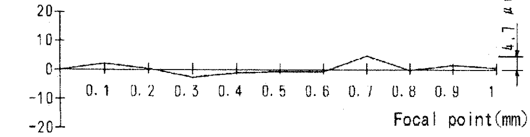

Fig.3 Fluctuation of principal point

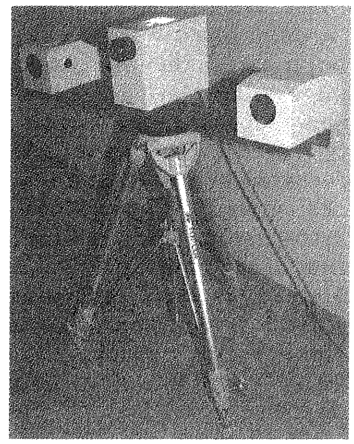

Fig.1 Image-acquiring part

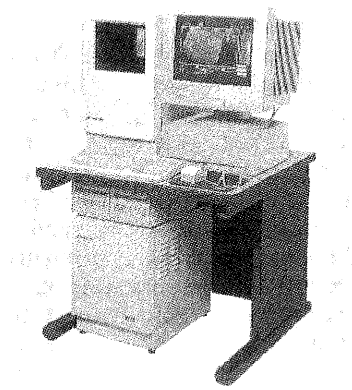

Fig.2 Image-analyzing part

2.2 Image-Analysis

For image-analysis we used the stereo-image workstation PI-1000, which we had developed as a digital plotter.

PI-1000 is an apparatus which conducts 3D measurement and plotting, employing the image information obtained through a high-resolution CCD camera (PC-1000), the image scanner (PS-1000) which we had developed and other CCD cameras. This apparatus, in fact, has a wide range of applicability for 3D measurement, such as civil engineering and industrial measurements etc.

The 3D measurement is conducted as follows.

First, when there is no particular texture or design on the object to be pictured, we project on the object a pattern design by pattern-projector and take its digital picture by a pair of high-resolution CCD camera. And we transfer its data now stored in optical disk or hard disk into the memory of PI-1000. PI-1000 then automatically rectifies the stereo image by rearranging the image data of right and left side on the epipolar line with the distance between the two cameras on base-bar as its base-length.

Next, the rectified image of the right and left side is displayed on a 3D image display, on which the floating marks and measurement results are superimposed.

There are two measurement modes: one is manual and the other is an automatic DTM (Ohtani, Ishii, 1992). The latter uses the stereo-matching by coarse-to-fine cross-correlation. This is a mode wherein a computer makes batch measurements by placing evenly spaced grid points on the left image to be processed by correlation.

Out of the calculated 3D coordinates we can obtain the stereo-contour-lines, perspective view and cross-section of the object.

Furthermore, since the measurement data can be output by the DXF format, our system a whole variety of applicability through AutoCAD*, CivilCAD(TOPCON), and the CAD system which is supporting DXF*.

2.3 Camera Calibration

For camera calibration we used the self-calibrating bundle adjustment software, which we had already developed. We have also developed a new software to detect automatically with sub-pixel precision the position of the targets placed on 3D test-field designed for calibration. This software establishes the correspondence between the image coordinates and the 3D coordinates of the targets already measured on 3D test-field by means of the orientation of single photograph. The software also detects the coarse position of the targets by means of image correlation as well as its fine position by detecting the edge with Laplacian-Gaussian filter.

This 3D test-field (Fig.4) was 1000 mm in both height and width, on which were placed 121 targets in 5 depth stages, i.e., 0mm, 100mm, 200mm, 300mm, 400mm and digitally photographed from 7 different positions (Cf:Fig.5). We used the 3D coordinates of the targets measured by a contact-type 3D measurement apparatus at the precision of $\pm 10\mu$ m.

Now, as to the details of camera calibration, confer to (Kochi, Ohtani, Nakamura and others 1995).

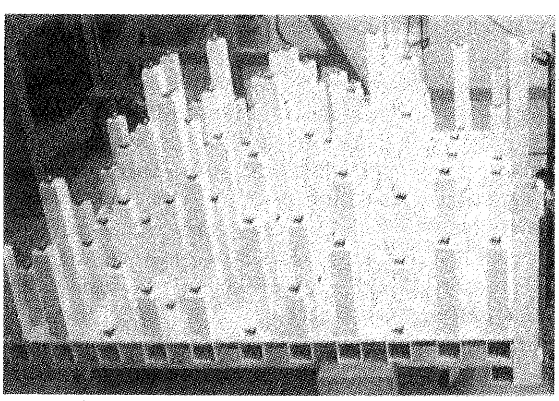

Fig.4 3D test-field

*AutoCAD,DXF are U.S. registrated trade marks of Autodesk, Inc.

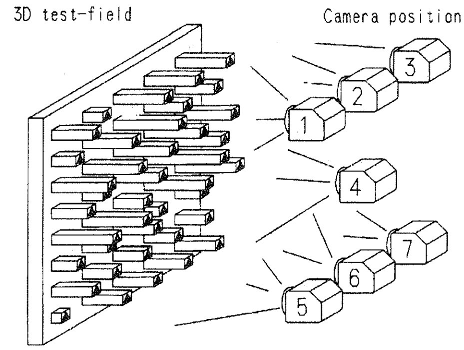

Fig.5 Configuration of image acquisition

3. SURFACE FLATNESS MEASUREMENT

Lately, the exterior characteristics of train body are increasingly diversified. For example, often times its surface is plain without design, or sandy with sandblasting or simply lustrous, or three dimensionally deep with curve, many of which characteristics make it difficult to measure by automatic stereo-matching.

Therefore, we first executed a preliminary testing with various simulated surfaces to see whether our surface measurement system really works and then applied it actually on a real train body.

3.1 Simulated Surface

We had already measured 80 points on a simulated surface of plain iron plate of 400mm × 300mm with the base length of 400mm and with the distance of 1000mm and obtained a satisfactory result of depth accuracy 0.39mm(rms) and target accuracy (Cf:(1)equation) 0.48mm (Kochi, Ohtani, Nakamura and others 1995).

This time we went further as to test-measure the sandblasted lustrous simulated surface of 300mm × 300mm with a round protrusion in the center to assess the precision (Cf:Fig.6).

On a sandy surface ordinarily the light from its source is diffused and reflected on the different parts of stereo images of the right and left cameras, thus causing the difference in the shading between the obtained images of two cameras. However, in our experiment it did not affect our stereo-matching much to our satisfaction.

The Fig.7 shows the cross section obtained from the measurement results processed through PI-1000. To confirm the accuracy of our system this result was compared with the result obtained by the contact-type-3D-measurement-apparatus of $\pm 5\mu$ m on 80 different points on the same surface. In our measurement the base length was 928mm with the distance of 1048mm. The experiment was quite satisfactory with the accuracy result of 0.23mm (rms) in depth measurement, compared with the targeted accuracy of 0.23mm.

The targeted accuracy is calculated by the following equation.

$$\delta Z=(H^2\times \delta p)/(f\times B) \qquad (1)$$

δZ:target accuracy (depth)
δp:accuracy of reading the image coordinates
H:distance between camera and object
B:base length
f :principal distance

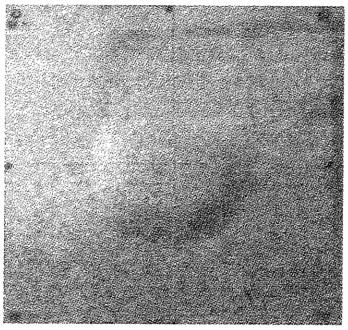

Fig.6 Simulated surface

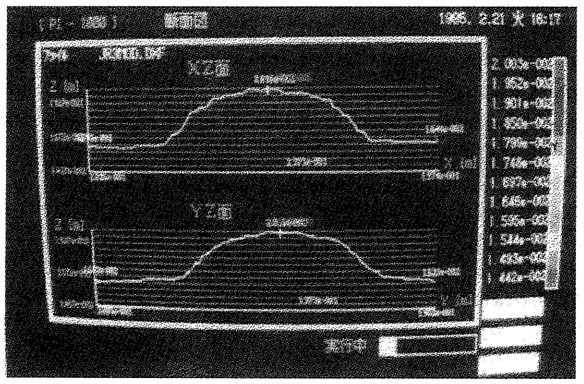

Fig.7 Cross section (PI-1000)

3.2 Application on a Stainless Train

We experimented our system on a stainless train body at Niitu Train Factory of East Japan Railway Co.Ltd. We measured the section 800mm × 800mm below the window. The measuring conditions were the same as 3.1. The Fig.8 shows the actual scene of measuring. Fig.9 shows the perspective view obtained by the automatic measuring processed by PI-1000.
As the stainless body is lustrous, it affects strongly the shading on the right and left images, thus forcing us to narrow the measuring area down to 600mm × 600mm. Nevertheless, with the exception of its periphery we could obtain a satisfactory data of 3D. The requested accuracy was 0.5mm, but we actually obtained the accuracy of 0.1mm (rms), fully satisfying the requested and targeted accuracy.

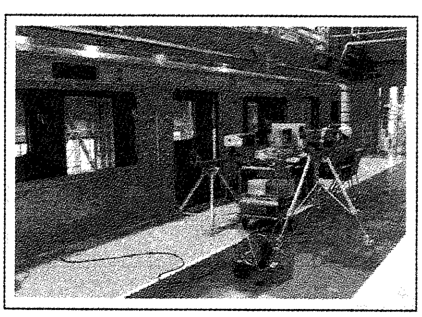

Fig.8 Scene of measuring

Fig.9 clearly shows a stripe-form protrusion of the train surface as well as the targets purposely placed thereon.

The mismatching on periphery was due to the fact that while the illuminating light of pattern design was almost saturated near the center (255 level), the amount of light decreased through shading down to almost 0 level, as it went to the periphery . In order to solve the problem, we are now developing the CCD camera (presently 256 level) of greater Gray scale resolution, thus widening the dynamic range.

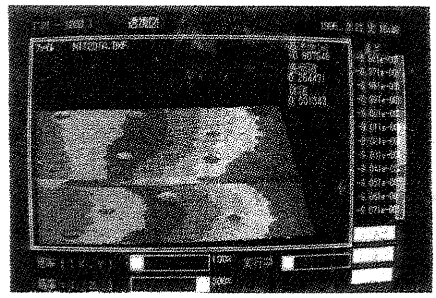

Fig.9 Perspective view (PI-1000)

4. MEASUREMENT OF NOSE CURVE

Basing on our research results so far obtained, we now proceeded to measure the 3 dimentional and larger surface. We first tested, therefore, on the simulated surface and then experimented on the actual nose of a bullet train (1000mm × 3000mm × 1000mm) of East Japan Railway Co.Ltd.

4.1 Simulated Surface

We made stereo-matching automatic measurement experiment on two simulated surfaces. One was a white flat plate of 1000mm × 1000mm. The other was a similar plate now curved with radius rate of 600mm. We measured two of them together simultaneously in the same measurement area, which was, therefore, 1000mm × 2000mm with the base length of 2000mm from the distance of 3000mm.
The Fig.10 shows the perspective view realized by our PI-1000 from the measurement results. The flatness and the curve are clearly observed.

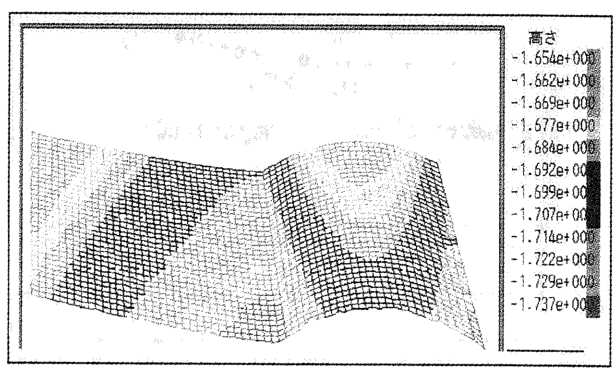

Fig.10 Perspective view (PI-1000)

4.2 Bullet Train (Shinkansen)

Then we proceeded to actually measure the nose of Shinkansen train by automatic measurement. The measurement was carried out in two different methods. First, it was made by a stereo-model from a single position. The other was made by a stereo-model moving through 5 different positions with control points to make successive adjustment. The Fig.11 shows 5 different positions of stereo-model and the checking points. To assess the accuracy of the checking points and to measure the control points we used IMS(Industrial Measuring System) MS-200. This system is to measure the 3D coordinates with triangulation, using the theodolite and subtense bar. Its relative accuracy is 1/8000.

The table 1. shows the results of each of the two different methods.

As to the requested and targeted accuracy of 1mm (Cf:(1) equation), the table 1.① shows that we have attained it fully.

In the case of table 1.②, as we did not change the camera's position on the base-bar and moved back the apparatus from the object, the distance became greater and the measuring area was narrowed, thus impeding the measuring plan to meet the requested accuracy. So, the accuracy was lowered, although the targeted accuracy was still satisfied.

Although we did not try this time, if we make a plan of measuring the area of 3000mm × 1000mm within the targeted accuracy 1mm, we are confident that it is possible to attain such precision even with the measurement by 1 stereo-model from a single position.

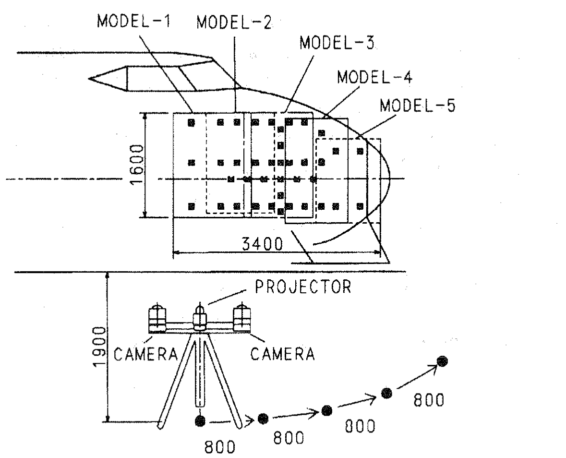

Fig.11 Positions of image-acquiring part and checking points

The time spent between camera operation and the end of analysis was about 1 hour for 1 stereo-model measuring from a single position (6000 points spaced 25mm from each other); whereas for the measuring from 5 successive positions it took about 7 hours (28000 points spaced 15mm from each other). In near future with the progress of algorithm and speeding-up of computer, we believe that it will become possible for 1 stereo-model operation to take only 15 minutes for 6000 points.

5. MEASUREMENT DATA MANAGEMENT AND APPLICABILITY TO CAD SYSTEM

PI-1000 can output the 3D data of analyzed result in the format of DXF file. DXF file is a standard data format, which can be input into almost any CAD systems and makes possible the mutual data usage between PI-1000 and other CAD systems. So, we believe it can also be applied to contrast composition of CAD data and design data.

The Fig.12 is a perspective view of 3D data of table 1.①. This perspective view was produced successively 1) first by changing the 28000 3D data obtained from PI-1000 into wire-frame, 2) second by inputting the data into AutoCAD through the DXF format, 3) third by applying to them rendering process on AutoCAD and 4) fourth by giving them 3D view angles. The Fig.12 shows very clearly the exhaust port and light section of the train and even the slight wrinkles of the paper covering the light are visible in an enlarged picture.

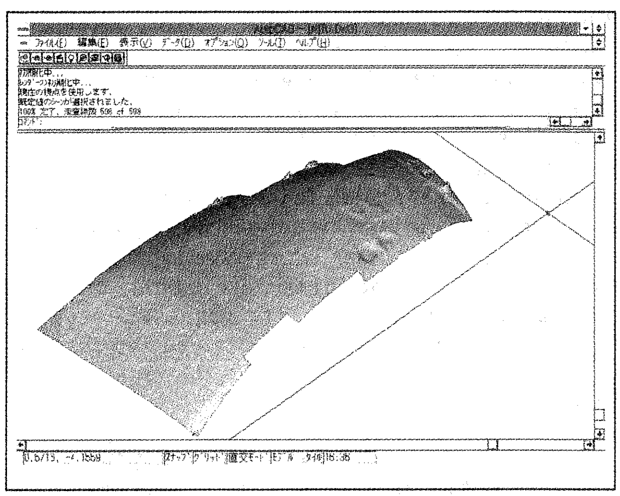

Fig.12 Perspective view (AutoCAD)

Table 1. Measuring conditions and measured results

Number of models	Measuring area (mm)	Distance (mm)	Base length (mm)	checking points	Control points	Target accuracy (mm)	Resulted accuracy (mm)	Point number in DTM	Total time
①5models	3400× 1600	1900	800	33	12	1.0	0.6	28188	7hours
②1model	2100× 2000	3000	800	27	0	2.7	1.8	6561	1hour

Again the Fig.13 is a contour-lined picture produced by processing through the data of the table 1.① into CivilCAD, a TOPCON surveying CAD.

The images which have gone through these processes and the images which have been processed through PI-1000 are possible to be output in the TIFF format, which is an image-format of wide applications. So, they can be input into the image editing software sold on the market and easily managed and edited. The examples of image outputting of our presentation this time were all processed through these tools.

The PI-1000 has a build-in device of 3D viewing by 3D display and can superimpose and display stereo images and measured 3D data. With this device we are able to check the correctness of 3D data, as well as to grasp visually the unevenness of surface without our being actually present at the spot.

The Fig.14 is an example of the superimposition of the stereo contour line image obtained by processing through PI-1000 onto the stereo image. Furthermore, by superimposing the measurement data onto the design data of CAD upon the 3D image display, we can make a contrast composition in 3 dimensions.

Though this time we did not do similar operation with Shinkansen experiment, we should like to do it at the first opportunity.

6. CONCLUSION

In this paper we have explained the general outline of our system, the experiments on the simulated surfaces, test results of measuring a real train body, and the examples of inputting measurement data into the CAD system. As to the test and experiments, we could obtain satisfactory results with regard to the targeted accuracy. Here we could also demonstrate the inputting process of such data into CAD systems as well as the different applicabilities of PI-1000, our stereo image workstation.

Our system enables quantitatively in short time a complex work from camera operation,

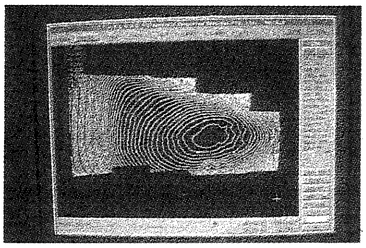

Fig.13 Contour lines (CivilCAD)

measurement of surface features and their final assessment, as well as a visual confirmation of the measurement results and the objects themselves. Furthermore, if we link it with CAD systems, a whole variety of application will become possible, such as comparison of the measurement data with design data, management of data etc.

In future, we are planning to further widen the applicable fields of this system, to increase its accuracy and to simplify the measurement system itself, as well as its application to CAD.

Finally, we should like to express our sincere gratitude to all the kindness and helps extended to us in our research works by East Japan Railway Co.Ltd.

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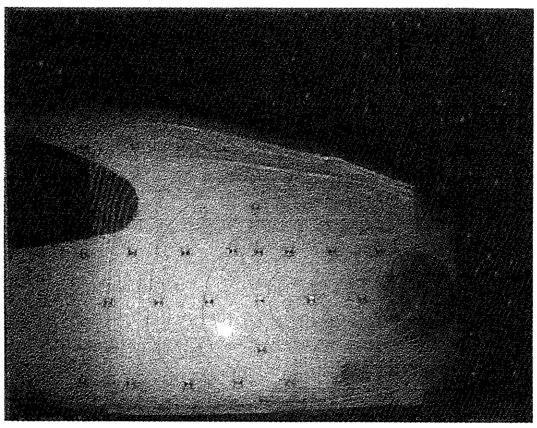

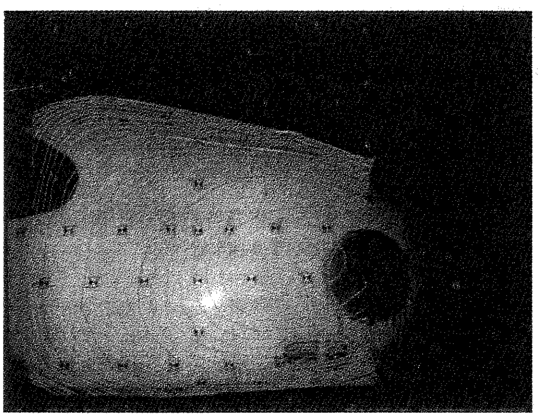

Fig.14 Stereo contour lines upon the nose of bullet train(left and right image)