A NOVEL MULTI-APERTURE DEVICE FOR SURFACE ROUGHNESS MEASUREMENT

Final report

Shizhuo Yin

January 1, 2000

U.S. Army Research Office

Contract/ Grant Number: G-DAAH04-96-1-0168

Department of Electrical Engineering
The Pennsylvania State University
University Park, PA 16802

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TABLE OF CONTENTS

3. LIST OF APPENDIXES, ILLUSTRATIONS AND TABLES

A. STATEMENT OF THE PROBLEM STUDIED

A1. Objective

The objective of this research project is to develop a novel multi-aperture based device for surface roughness measurement. This novel device can provide U.S. Army a handy tool for precisely measuring workpiece (e.g., pistons) surface roughness, for which a better product (e.g., guns and tanks) can be made. Thus, this research project can enhance the overall manufacturing capability of U.S. industries, which in turn may benefit both the military and civilian users.

A2. Background

For many precise mechanical parts (e.g., bearings, block gauge, pistons, etc.), it is very important to continuously measure the micro-surface roughness during the manufacturing process. Thus, it is extremely helpful if a handy, cost effective, *in situ* measuring tool is available. Although some interferometric [1-2] or laser scattering techniques [3-4], in principle can be used for precisely measuring micro-surface roughness, they are to some extent expensive, not handy, and difficult for *in situ* operation, which limit their practical applications.

On the other hand, many scientific inventions are based on the application of biological principles to the study and design of engineering system, which is known as BIONICS [5]. For example, one of the very interesting consequences for most compound eye insects is that the diameter of each lens of a compound eye (as shown in Fig. 1) is about equal to the lateral coherence distance of the sunlight (about 50 μm) [6-8]. Thus, the sunlight behaves like a spatially coherent light source for most of the compound-lens animals, for which it exists an one-to-one relationship between the direction of the light beam and the locations of the retina focal sport. Thus, the direction of the sun beam can be used as the navigational reference for some insects [9].

From above discussion, one can see that it is very important to have a spatially coherence system. In fact, the highest axial discrimination capability of confocal microscope (as shown in

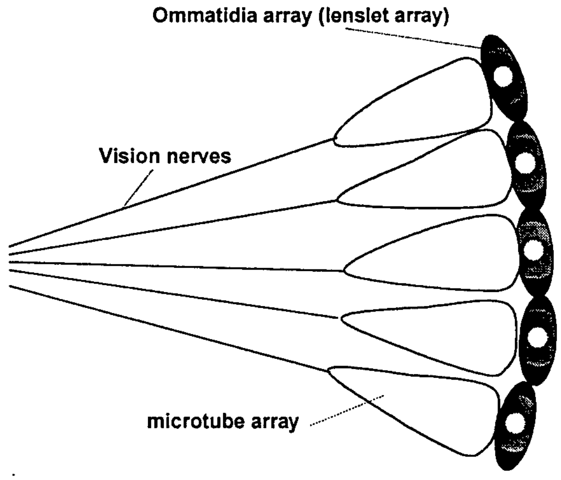


Fig. 1.Compound eye structure

Fig. 2) comes from the high spatial coherence of the system (due to the use of pinhole and point light source [10]. Without the high spatial coherence of the system, one can not distinguish the in focus and out of focus light so that the system would not have high axial discrimination capability. Note that, the high axial discrimination capability of confocal system has been used to measure surface profile [11]. Unfortunately, to obtain a two-dimensional surface profile, complicated scanning process is required for the conventional confocal microscope system, which makes the system cumbersome, expensive, and difficult for *in situ* real-time operation.

Obviously, to increase the speed of obtaining 2-D profile of a surface, multi-aperture is a reasonable approach. However, it is extremely difficult to align the system by directly applying multi-aperture (compound eye) structure to conventional microscope system. For example, if one uses the pinhole array based multi-aperture system, one has to carefully align lenslet array, and pinhole array. When the number of the element of the array becomes large (e.g., 100 x 100), it is extremely difficult to align these three arrays in micron accuracy. Evan one can do that, the system may not be robust, which limits the practical *in situ* applications. In addition, there are may be cross-talks among different channels. To solve this problem, let us go back to look at the compound eye structure of insects (as shown in Fig. 1), in which microtube instead of conventional pinhole is used to isolate each channel. This interesting microtube structure helps us to develop a novel microtube array based multi-aperture imaging device, which can be used for precise surface roughness measurement.

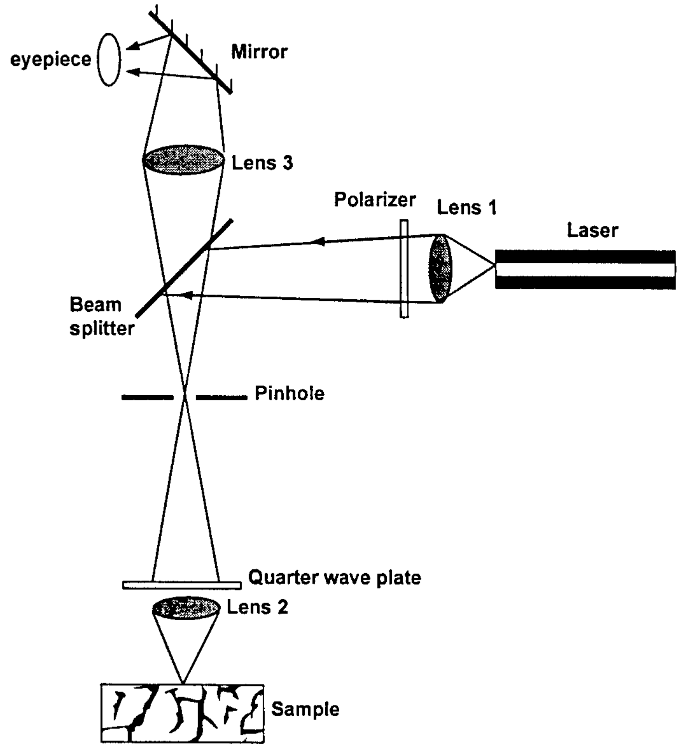


Fig. 2. A simplified diagram of confocal microscope

B. SUMMARY OF THE MOST IMPORTANT RESULTS

B1. Design a novel multiple aperture based roughness measurement system.

The technical approach is to convert the surface roughness information (i.e., phase information of an object) into light intensity fluctuation via a novel multi-aperture device. This device basically consists of two key elements, a microtube array and a micro lenslet array. The basic principle of this system is based on the well known fact that only the collimated light beam can pass through the microtube without suffering major attenuation as shown in Fig. 3.

4. BODY OF REPORT

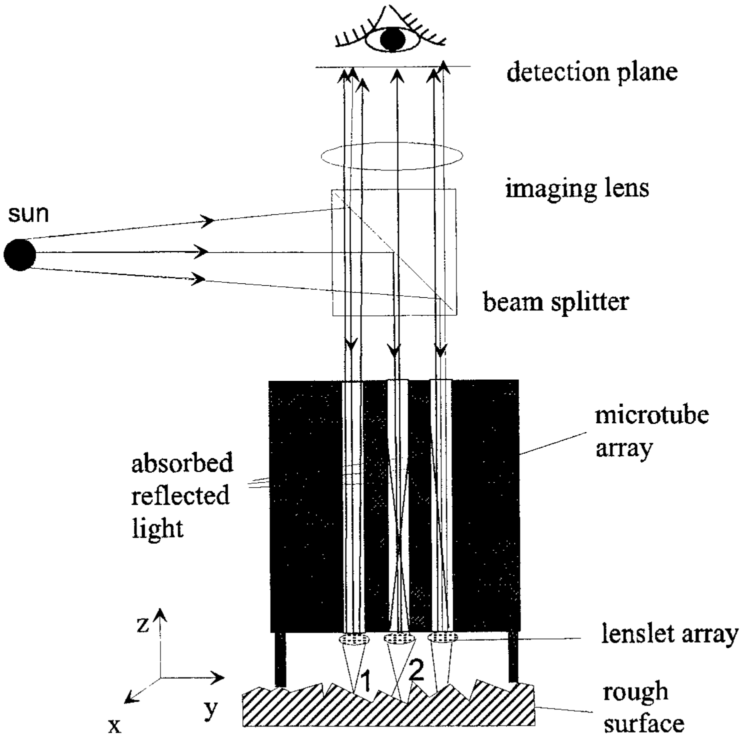


Fig. 3. A multi-aperture imaging device

If a specific area of a rough surface is located at the focal plane (i.e., in-focus case, **POSITION 1**) of the microlens, the reflected light from that area will be a backward propagated collimated beam after passing through the microlens without serious attenuation within the microtube. However, if an area of a rough surface is located at the out-of-focus position (i.e., **POSITION 2**), the scattered light beam will not be a collimated beam after passing through the microlens. Then, it will be partially absorbed by the inside black wall of the microtube. Thus, the variation of the rough surface can be converted into the light intensity fluctuation.

The major advantages of this proposed multi-aperture device are the real-time *in situ* measurement capability, self-alignment, robustness, and large measuring dynamic range (from tens of nanometers to tens of microns). Thus, this device may play an important role in the *in-situ* inspection of industrial workpieces.

B2. Fabricate a prototype of multiple aperture based surface roughness measurement device

B2.1. Material and component preparation

To make this program successful, first, we have looked into all necessary materials and components that need to be prepared and purchased. Without this step, we can not start doing any experiments. There are three major components that have been investigated.

B2.1.1. Micofinish comparator

The first one is a standard microfinish comparator, as shown in Fig. 4.

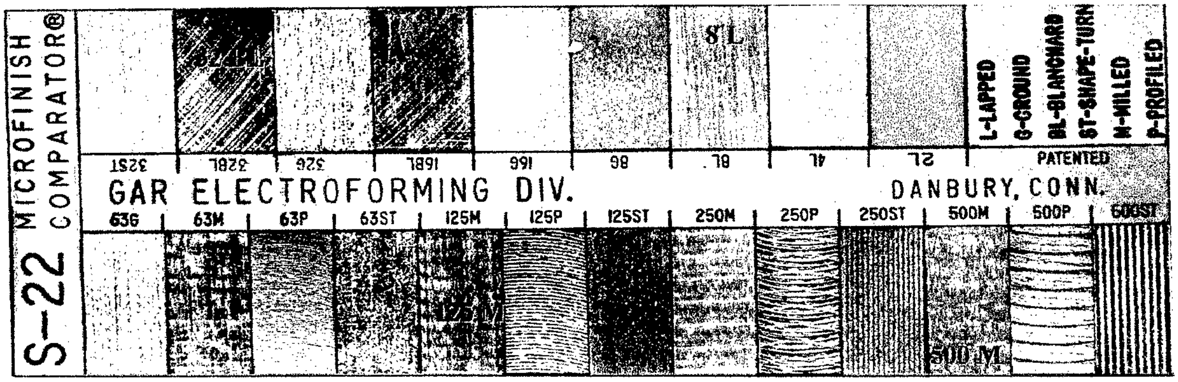


Fig. 4. A microfinish comparator (model No. s-22)

This comparator is a standard surface roughness scale for surface quality control, which is made by a dual electroforming process wherein nickel is electrodeposited to provide an exact reproduction in intricate detail. There are twenty two replicated machined surface finish specimens with examples of six different machining processes: lapped, ground, blanchard ground, shape-turned, milled and profiled - ranging from 0.05 μm to 12.7 μm. This comparator provides industry with established flat surface roughness specimens for visual and tactual comparison.

In this project, this comparator is used to test and calibrate the performance of our multi-aperture surface roughness measurement device.

B2.1.2. A microtube array.

A black glass made microtube array has also been purchased from Collimated Holes, Inc., as shown in Fig. 5. The dimension of this array is as following: The total diameter of the array is about 25 mm and its thickness is about 0.5 mm. The diameter of each hole is about 25 microns.

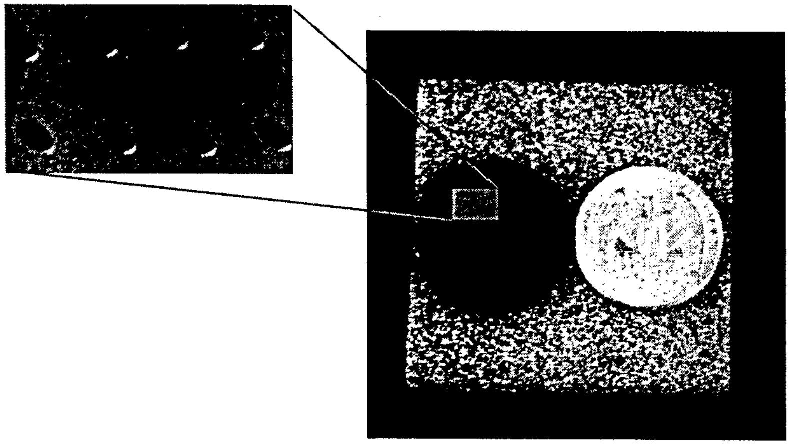


Fig. 5. A microtube array.

To make the experiment easier, a 10x10 microtube array with larger size hole diameter was also fabricated as shown in Fig. 6. The size of each hole is about 350 μm and the length of each hole is about 25 mm. The distance between adjacent holes is about 400 μm.

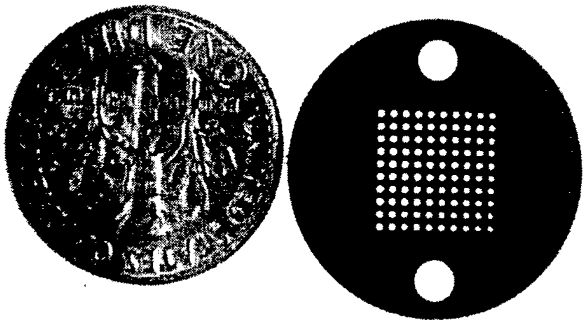


Fig. 6. A 10x10 microtube array. Diameter of each hole = 350 μm,

and length of each hole = 25 mm, distance between adjacent hole = 400 μm.

B2.1.3. A micro lenslet array

The third key component is a micro lenslet array sampler (manufactured by United Technologies Adaptive Associates), as shown in Fig. 7.

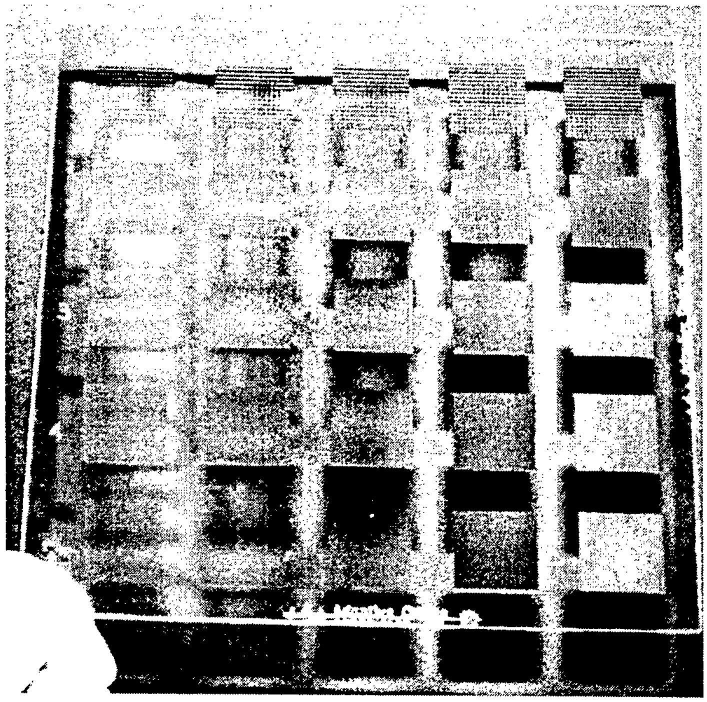


Fig. 7. A micro lenslet array sampler.

This sampler consists of 25 monolithic lens arrays compression molded in a 6" x 6" acrylic sheet. Each array size is 18 x 18 mm. The aperture format of the arrays is square. The parameters for each array are tabulated in Table 1.

A	B	C	D	E
f = 29.3 mm D = 1000 µm 18 x 18	f = 20.5 mm D = 1000 µm 18 x 18	f = 16.5 mm D = 1000 µm 18 x 18	f = 12.75 mm D = 1000 µm 18 x 18	f = 10.0 mm D = 1000 µm 18 x 18
f = 20.1 mm D = 750 µm 24 x 24	f = 13 mm D = 750 µm 24 x 24	f = 7.5 mm D = 750 µm 24 x 24	f = 6 mm D = 750 µm 24 x 24	f = 4 mm D = 750 µm 24 x 24
f = 16.5 mm D = 500 µm 36 x 36	f = 10.4 mm D = 500 µm 36 x 36	f = 5.0 mm D = 500 µm 36 x 36	f = 2.5 mm D = 500 µm 36 x 36	f = 1.2 mm D = 500 µm 36 x 36
f = 10.7 mm D = 400 µm 45 x 45	f = 5.2 mm D = 400 µm 45 x 45	f = 3.0 mm D = 400 µm 45 x 45	f = 2 mm D = 400 µm 45 x 45	f = 1 mm D = 400 µm 45 x 45
f = 7.9 mm D = 200 µm 90 x 90	f = 5 mm D = 200 µm 90 x 90	f = 2.0 mm D = 200 µm 90 x 90	f = 1 mm D = 200 µm 90 x 90	f = 0.5 mm D = 200 µm 90 x 90

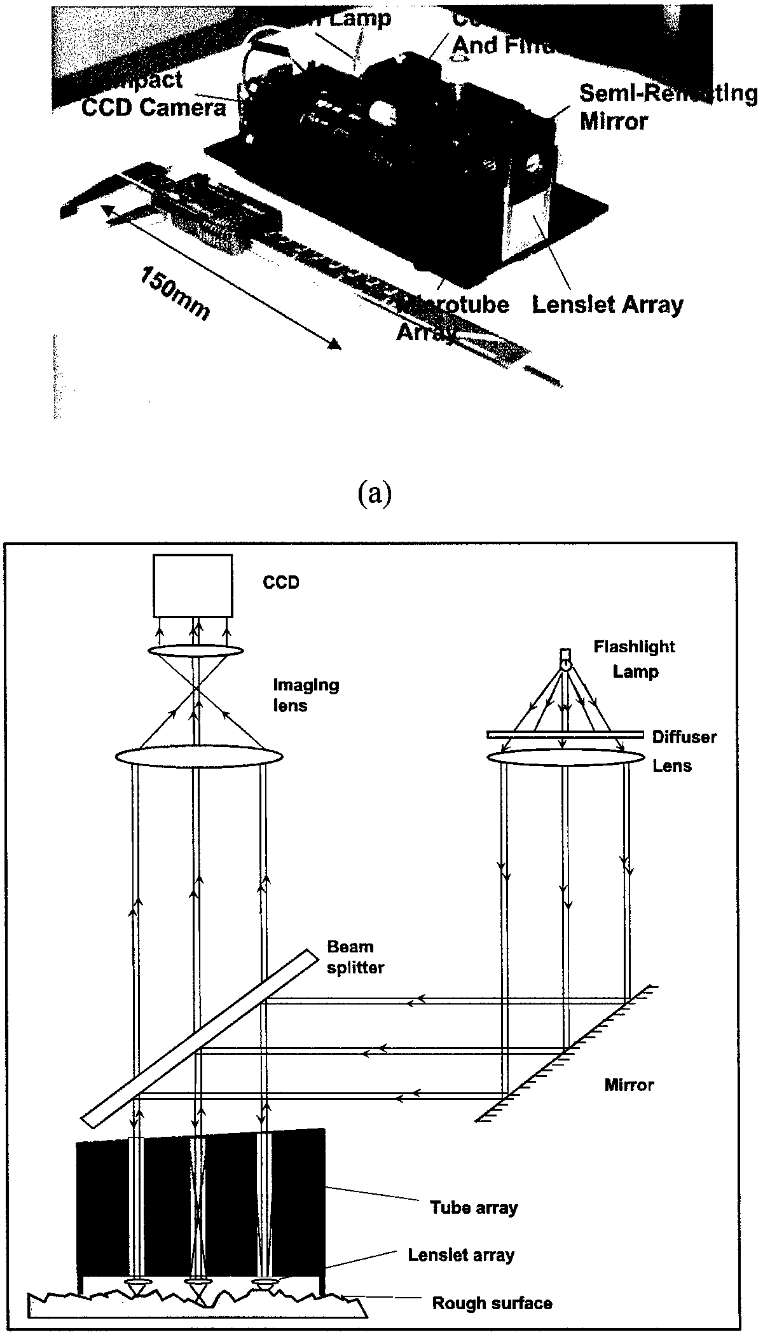
Table. 1. Parameters of array sampler.

In each box, the f represents the focal length of each lens, D represents the diameter of each lens, and the third line represents the number of lenses in each array.

This sampler is used to produce a set of lenslet array and combine it with the microtube array.

B2.2. Fabricate the prototype of multiple aperture system

A demo prototype was also been fabricated during this period of research. Figure 8a shows the picture of the built prototype and Fig. 8b depicts the corresponding architecture diagram.



(a)

(b)

Fig.8. A prototype of multiple aperture system

This prototype comprises a microtube array, a lenslet array, and a semi-reflecting mirror, in which the microtube and lenslet array are fixed together. The light beam from a flashlight lamp is used as the point light source. After passing a diffuser and a lens, it is transformed into approximate parallel beam. This partially parallel light beam is reflected by a semi-reflecting mirror, then pass through a microtube array and lenslet array, and finally incidents on the surface whose roughness is to be assessed. Only the reflected beam from those parts of the object that are located in the focal plane will be a backward propagated collimated beam after passing through the lens again with rarely absorption by the inside black wall of the microtube. Whereas the reflected beam from parts that are outside the focal plane will not be a collimated beam and will be heavily absorbed. Therefore, the fluctuation of the rough surface can be converted into the intensity distribution on the output plane of the system. The light intensity on the output plane is captured by the CCD array camera and transferred to a microcomputer for the data processing. After compared with the data on workpiece from calibrated standards of surface roughness, the surface roughness information of the measured workpiece are obtained. To reduce the measurement errors induced by the variation in the focus plane along the lenslet array and the difference among the microtube array, a standard plane mirror is stored as a reference that will be subtracted from each measured topography of the rough surface.

Notice that, the roughness of a surface is defined as the standard deviation of the surface profile. In order to measure the roughness, first of all, we have to obtain the sampled data of the two-dimensional lateral light intensity distribution, which can be automatically obtained by using the above array structure. The number of elements in an array decides the number of sample points. The number of elements in the above array is 10 x 10. Thus, there are enough data for doing statistical data processing so that the standard deviation of the sampled data is close enough to the standard deviation of the rough surface.

B2.3. Test the performance of the fabricated prototype

Figure 9 shows how to use the fabricated prototype measuring the surface roughness of a comparator.

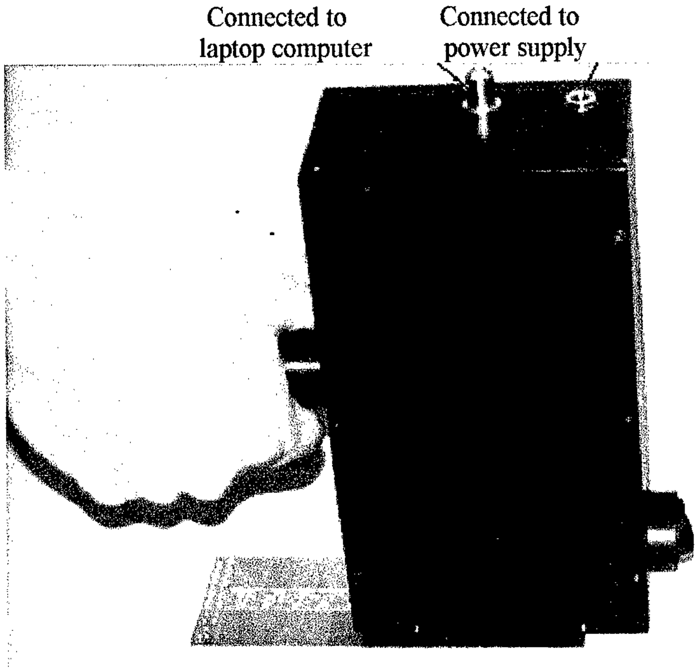


Fig.9 Using the multiple aperture device for on-line surface roughness measurement

Before measuring the surface prototype of the comparator, the axial discrimination capability of the system was evaluated. During the experiment, the comparator mounted on the linear stages moved along the axial direction, which can be controlled by computer, and the central light intensity imaged on the CCD camera is recorded at a set of longitudinal location of the comparator.

To achieve good signal to noise ratio, following issues were carefully considered during the experiments. First, we carefully adjusted the longitudinal direction of the stage movement so that it will be precisely parallel to the direction of the probe laser light. Second, we carefully adjusted the comparator to guarantee that it will be perpendicular to the direction of the probe laser light. Third, the location of each scanning along the axial direction was accurately determined. Finally, we also optimized the acquisition time of measurement in the software program so that a better efficiency of measurement was achieved.

Figures 10 to 13 shows the normalized light intensity as a function of axial defocus distance for different focal lengths. It can be seen that the resolution for detecting the position of the comparator improves dramatically with shorter focal length. With the 2.0mm focal length, the half-width of the light intensity is about 400μm, as shown in Fig. 10. Suppose that the 8-bits CCD be used to take the picture, the light intensity can then be digitally divided into 256 levels. Therefore, under this circumstance, the minimum movement of the comparator along the longitudinal direction, which can be detected by the CCD camera, is about 1.6μm. However, if we use the 0.2mm focal length lens, the half-width of the light intensity decreases to about 10μm. And the detecting resolution of this system can reach 0.05μm, as shown in Fig.13. In other words, 0.05 μm axial direction resolution was achieved in this period of research.

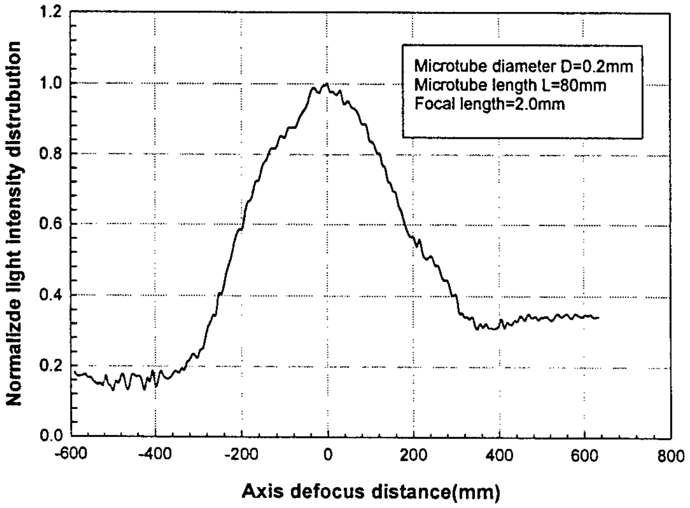


Fig.10. Normalized light intensity as a function of longitudinal location of the comparator. The focal length is 2.0mm.

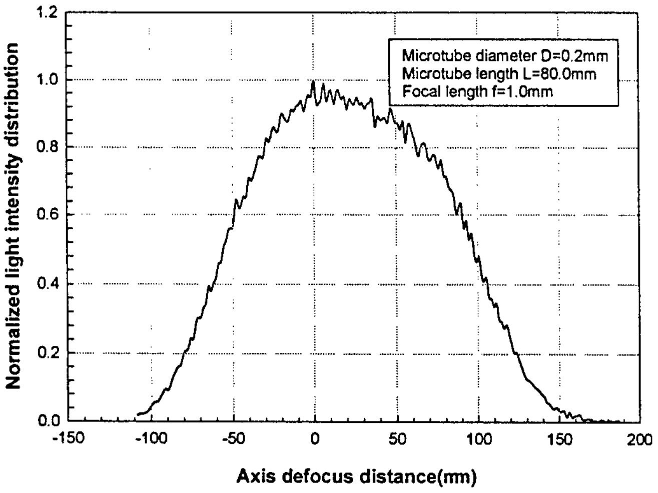


Fig.11. Normalized light intensity as a function of longitudinal location of the comparator. The focal length is 1.0mm.

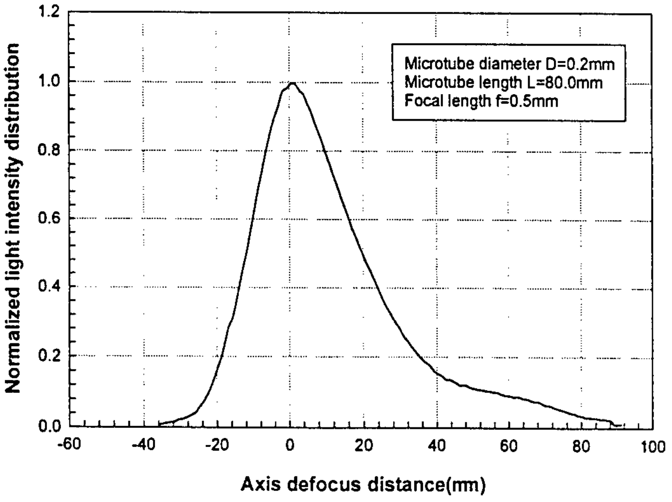


Fig.12. Normalized light intensity as a function of longitudinal location of the comparator. The focal length is 0.5mm.

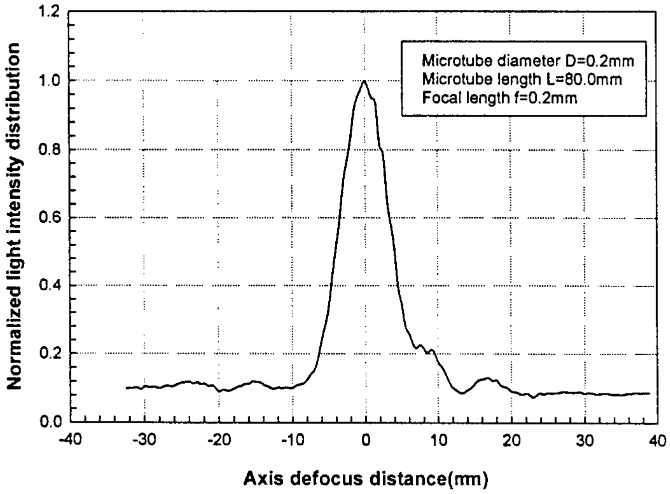
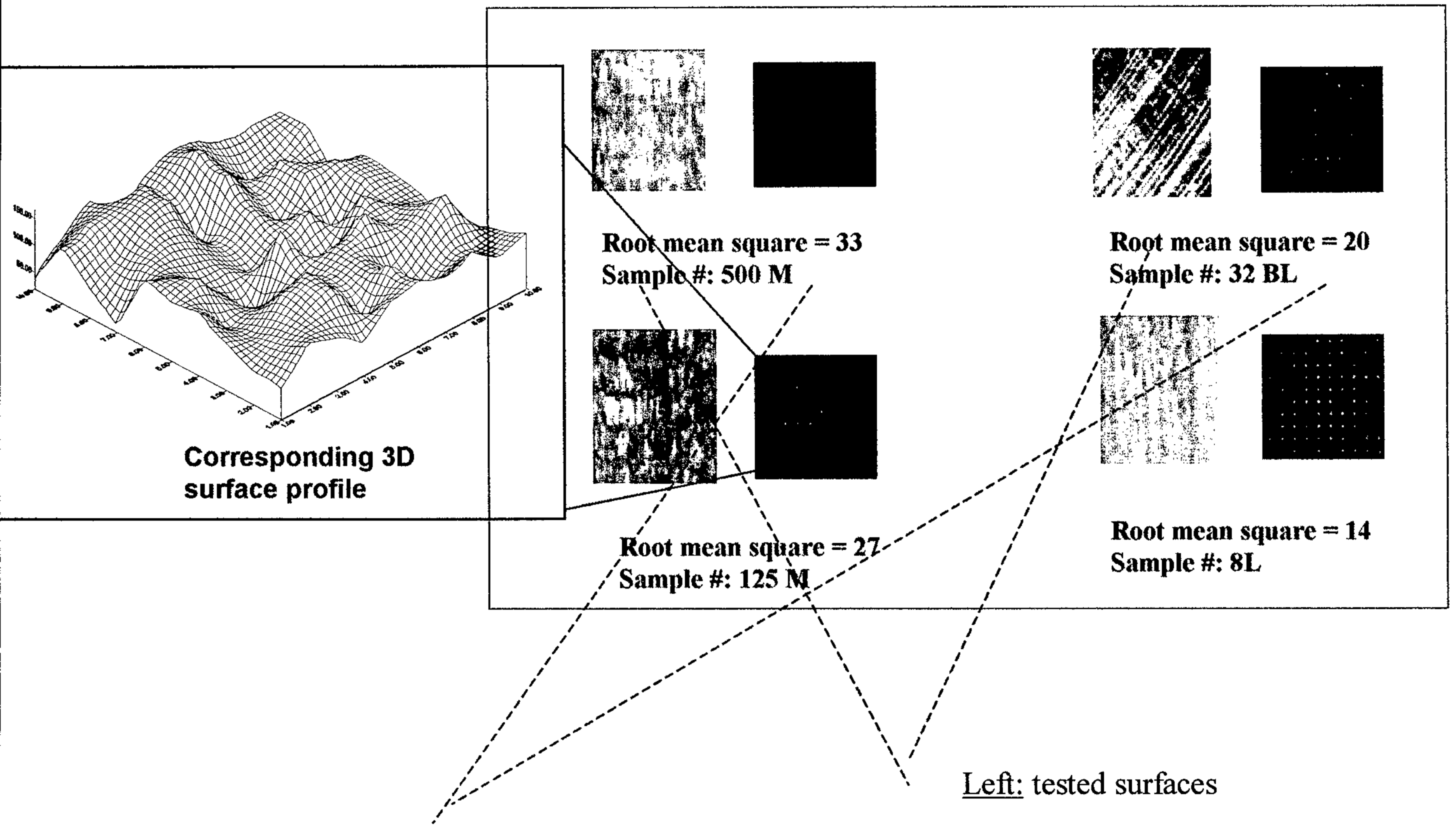


Fig.13. Normalized light intensity as a function of longitudinal location of the comparator. The focal length is 0.2mm.

In the experiment, microtube length L was 80.0mm. This is because the lens diameters D of the lenslet array are 0.2mm, 0.4mm, 0.5mm and etc. According to Rayleigh's criterion, the minimum lateral distance of two spots on the image, which can be resolved, will be in the order of $\lambda f/D$, where λ is the light wavelength. In order to obtain the spatial resolution by using the microtube, we have to let $fD/L<\lambda f/D$, here f is the focal length of the lens. Therefore, the microtube length L must be larger than 80.0mm (here the wavelength λ is supposed to be around 0.5μm), if we use the 0.2mm diameter lens and microtubes. And about 320 mm long microtube has to be used for 0.4 mm diameter lens. In addition, since 320mm length is too long compared with the original goal such as "portable, compact size system for the surface roughness measurement", we have to discard these microtubes which are larger than 0.2mm.

We also found, from the experimental results, that although with the shorter focal length, the longitudinal resolution becomes better, but the dynamic range of the system becomes more limited. That means for different roughness surface samples, we have to use different focal length lens. From Figs.10-13, one can also see that the peaks of the light intensity are not symmetrical, as predicted theoretically. But the curves are not totally same as the ones derived from the equation in our original proposal. We believe that this inconsistency is major due to the simplified model in our original proposal. For example, we only use the simple geometrical formula. In addition, we also omitted many factors that may affect the resolution of the setup. For instance, we assume that the oblique light is totally absorbed by the black microtube. In fact, the reflection light from the surface of the sample may not be totally absorbed by the inside black wall of the microtube in real case, and it may travel through the microtube to reach the CCD camera.

To measure the surface roughness, four surface samples are selected from the standard comparator (as shown in Fig. 4) as the test samples. The item numbers of these four samples are 8L, 32BL, 125M, and 500M, respectively. The smaller the normal (e.g., 8L), the smoother the surface is. In other words, the smaller number corresponds to a smaller standard deviation. Figure 14 shows the measured experimental results. From these results, one can see that the smoother the surface, the more uniform the light intensity distribution is. Thus, there is a one-to-one relationship between the surface roughness and the standard deviation of the output light intensity distribution. The experimental results from this demo prototype demonstrated the feasibility of the proposed multi-aperture system.



Left: tested surfaces

Right, output light intensity distribution detected by the CCD camera, each spot correspond to one microtube

Fig. 14. Experimental results

B2.4. Surface profile measurement

Besides the roughness measurement, we also further develop this device by combining the transversal scanning and microtube structure so that it can be used to measure the profiles of the standard roughness comparator. As the out-of-focus light intensity corresponds two positions along axial direction, we need to find the position that corresponds the maximum light intensity on each spot of the standard comparator. Therefore, we use x-z stage, mentioned before, for measuring the profiles of the standard roughness comparator. Here the x-axis is the scanning direction along the surface of the comparator, while the z-axis is axial direction for scanning the maximum light intensity. The direction of z-axis is absolutely parallel to the direction of the probe laser light. Figure 15 shows the results of our measurement. For the purpose of verification, the surface profile of same sample was also measured by the mechanical stylus probe, as shown in Fig. 16. By comparing these two figures, one can clearly see that two profiles agree very well. Thus, by combining the transversal scanning and microtube structure, the proposed system can also be used non only to measure the surface roughness, but also determine the surface profile.

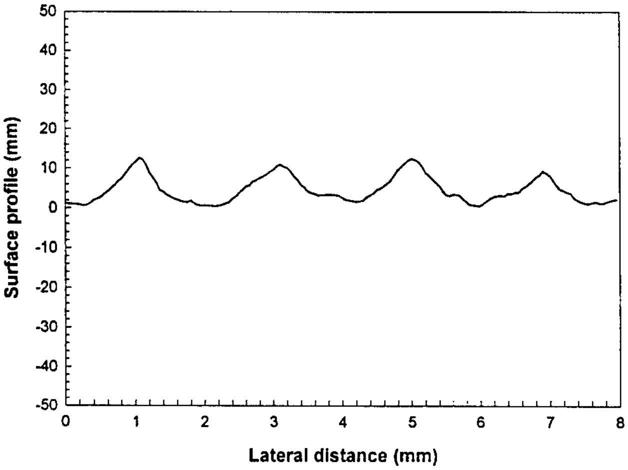


Fig.15. Reconstructed profile of the sample comparator using proposed microtube structure

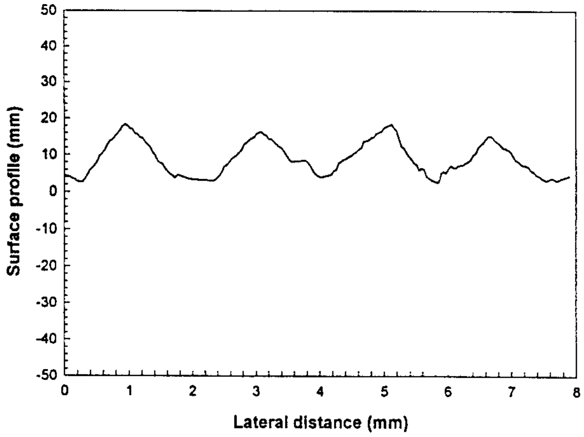


Fig.16. Reconstructed profile of the sample comparator using stylus profiler

C. LIST OF ALL PUBLICATIONS AND TECHNICAL REPORTS

1. S. Yin, J. Li, and M. Song, "Surface profile measurement using a unique microtube-based system," Optics Communications, 168, pp. 1-6 (1999).

2. S. Yin, P. Purwasomarto, T. Lu "Development of a real-time one-step 3D camera for the inspection of surfaces of automotive industry," Proceedings of 32nd International Symposium on Automotive Technology and Automation (1999).

3. S. Yin, J. Li, and M. Song, "A unique surface roughness measurement system based on microtube and micro lenslet array," Proceedings of Optical Society of America Annual Meeting'98, ThJ3, p. 123, Baltimore, Maryland (1998).

D. LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL SHOWING ANY ADVANCED DEGREES EARNED BY THEM WHILE EMPLOYED ON THE PROJECT

Dr. Shizhuo Yin: Principal Investigator of the project. 50% summer and 25% academic of his salary has been supported by this project.

Mr. Jiang Li: Research Assistant. He has been fully supported by this research project.

Mr. Jiangzhong Zhang: Research Assistant. He has been partially supported by this research project. He won the Ph.D. degree in Electrical Engineering in May 1997.

Mr. Chun-Te Li: Research Assistant. He has been partially supported by this research project. He won the Ph.D. degree in Electrical Engineering in May 1998.

Mr. Minho Song: Research Assistant. He has been partially supported by this research project.

5. REPORTS OF INVENTIONS (by title only)

We have filed a patent application through The Pennsylvania State University. The title of the inventions is "A portable, compact size cost-effective, fast speed system for the surface roughness measurement."

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7. APPENDIXES

Appendix 1: Standard Form 298

REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE Jan. 1, 2000	3. REPORT TYPE AND DATES COVERED May 1, 1996 to Dec. 31, 1999, Final

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12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.	12 b. DISTRIBUTION CODE N.A.

13. ABSTRACT (Maximum 200 words)

The objective of this research program is to develop a novel multi-aperture device for the surface roughness measurement. The successful fabrication of this novel device can provide the U.S. Army a handy, *in situ*, cost-effective, real-time tool for the precise measurement of workpiece surface roughness. We have accomplished all the proposed research tasks. Specifically, (1) design and fabricate a novel multiple aperture surface roughness measurement prototype. (2) The performance of the prototype was carefully evaluated. In particular, the depth resolution as a function of the focal length of the microlens was analyzed. It was found that the depth resolution as high as 0.05 μm could be achieved. (3) Combine the microtube structure with x-direct transversal scanning. Therefore, much more data points can be obtained. In addition, not only the surface roughness but also the surface profile information can be detected. A patent on this technique was filed. Hopefully, an useful commercial product could be built based on the achievements of this research project, which will benefit both the military and civilian users.

14. SUBJECT TERMS Surface roughness measurement, multi-aperture microtube array, lenslet array, three-dimentional surface profile measurement, computer controlled scanning.	15. NUMBER OF PAGES 20
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