The Design of a 3-D Surface Geometry Acquisition System for Highly Irregular Shaped Objects: with Application to CZ Semiconductor Manufacture

Vivek A. Sujan and Steven Dubowsky
Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, MA 02139

Abstract

A Robotic System is being developed to automate the crucible packing process in CZ semiconductor wafer production. It requires the delicate manipulation and packing of highly irregular polycrystalline silicon nuggets, into a fragile fused silica crucible. For this application, a dual optical 3-D surface geometry measuring system that uses active laser triangulation has been developed and successfully tested. One part of the system measures the geometry profile of a nugget being packed and the other the profile of the nuggets already in the crucible. A resolution of 1mm with 15 KHz sampling frequency is achieved. Data from the system is used by a packing algorithm to determine optimal nugget placement. The system is shown to achieve high production rates, required precision and cost effectiveness.

1 Introduction

The requirements for growing large single device-grade semiconductor crystals are very stringent. Extraordinary low impurity levels, on the order of 1 part in 10 billion, are required. Such low contamination levels require careful handling and treatment of the material at each step of the manufacturing process. During the widely used CZ semiconductor wafer production process, highly irregular shaped polycrystalline silicon nuggets (see Figure 1) are packed into a fused quartz crucibles [5]. The nuggets range in weight from a few grams to about 300 grams. Along with avoiding contamination, protecting the crucible from damage and following complex packing density rules are key constraints during the process [6]. Currently this tedious task is performed manually. Clearly, this important task would benefit from automation. Since each nugget has unique size and shape a robotic solution is appealing and is currently being developed [13]. A key technical component is a vision system to provide the 3-D surface geometries of the individual nuggets before they are placed in the crucible and of the nuggets that have already been packed.

Machine vision to provide 3-D surface geometry information has been widely studied and applied [10]. Methods to obtain visual data 3-D of an object can be broken down into triangulation, holographic interferometry (phase shift measurement), radar (time of flight), lens focus and Moiré techniques [2, 3, 10]. A detailed review in which several of the above methods are discussed and compared has been published [11]. All methods suffer some limitations or others, such as blind regions, computational complexity, limited to highly textured or structured scenes, limited surface orientation, and/or limited spatial resolution. Active triangulation eliminates many problems provided an intense enough light source is available. It can capture the third dimension through model-free range measurement. This can be very useful in 3-D scene analysis. It can resolve many of the ambiguities of interpretation arising from lack of correspondence between object boundaries and inhomogenities of intensity, texture and color found in other methods [2, 3, 4, 11, 15].

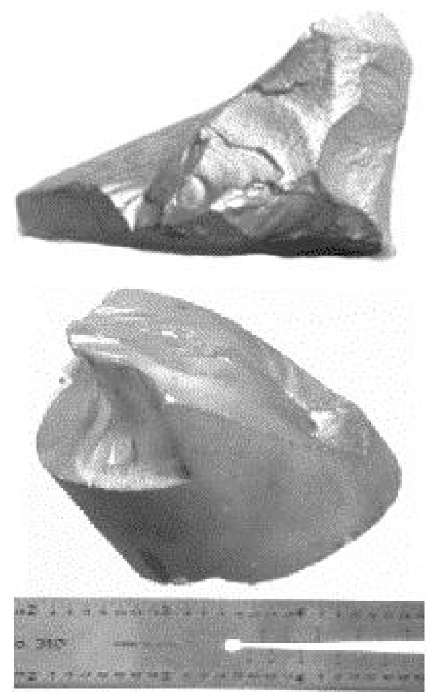

Figure 1: Typical polycrystalline silicon nuggets

The CZ process contains constraints, such as a complex environment, cost and compactness, which make the practical design of 3-D surface geometry acquisition very challenging. In this paper the design of a 3-D vision system using active laser triangulation with CCD cameras to meet the stringent requirements of the CZ process is presented. One system element is for surface geometry acquisition (SGA) of the landscape of nuggets in the crucible and the second for the nugget geometry acquisition (NGA). The paper outlines the design, implementation and calibration of the systems. It also presents experimental results that show it can meet the requirements of CZ process automation.

2. System Design

2.1 Point wise Triangulation Using One Camera

The basic design is shown in Figure 2. A single camera is aligned along a Z-axis with the center of the front node of the lens located at (0,0,0) giving the origin of the camera coordinate frame. At a baseline distance b to the left of the camera (along the negative X-axis) is a laser that projects a plane of light at a variable angle α relative to the X-axis baseline. The point (x, y, z) in the scene is projected onto the digitized image at the pixel (u, v), controlled by the focal length of the lens, f (see Figure 2). The measured quantities (u, v) are used to compute the 3-D coordinates (x, y, z) of the illuminated scene point:

$$\begin{bmatrix} x & y & z \end{bmatrix} = \frac{b}{f \cdot \cot(\alpha) - u} \begin{bmatrix} u & v & f \end{bmatrix} \qquad (1)$$

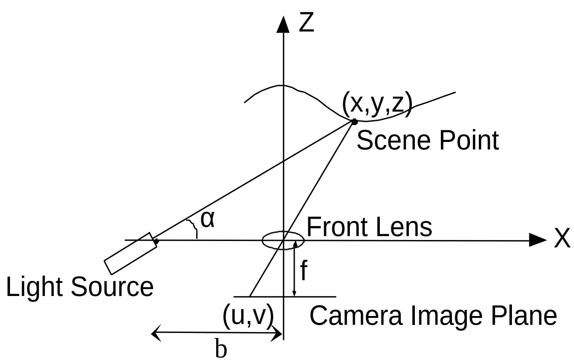

Figure 2: Project and Viewing Schematic

For any given focal length, f, and baseline distance, b, the resolution of this triangulation system is only limited by the ability to accurately measure the angle α and the image plane coordinates (u and v). The X and Y system (δX, δY) are given by:

$$\frac{R}{Detector \quad resolution} \qquad (2)$$

where R is the width of the projected image onto the detector. The depth resolution, δZ, given an incident laser angle α, image width W, and n-pixel detector resolution is given by:

$$\delta Z = (W \tan \alpha) / n \qquad (3)$$

The value of the resolutions (δX, δY, δZ) may differ for the two image plane coordinates (u,v).

2.2. Surface Geometry Acquisition (SGA)

The CZ prototype laboratory system layout is shown in Figure 3. The crucible is scanned while the manipulator is out of the Field Of View (FOV). The scanning consists of two phases (i) a low resolution scan that is updated every 10 nugget placement cycles and (ii) a high-resolution scan every nugget placement cycle in the area that was manipulated. The high-resolution scans are patched together to give a larger high-resolution map of the entire crucible. The design requirements for the prototype system design are:

- X, Y, Z resolution of 1mm
- Clearance height of the SGA greater than the manipulator height
- Minimization of blind regions and obfuscation due to crucible walls

Based on these requirements the SGA system parameters outlined in Figure 4 and Table 1 were developed. A crude / low resolution global scan gives a XY resolution of 1.5 cm and takes one second to process for an 18”diameter crucible. Further resolution improvement is achieved by allowing longer scan times. A higher resolution local scan (6” wide band) gives XY resolution of 1mm and takes 4.5 seconds to process. All times are based on standard video frame rate of 30 frames/s. These times are comparable to the times required for the manipulator actions of getting a new nugget and bringing it to the crucible.

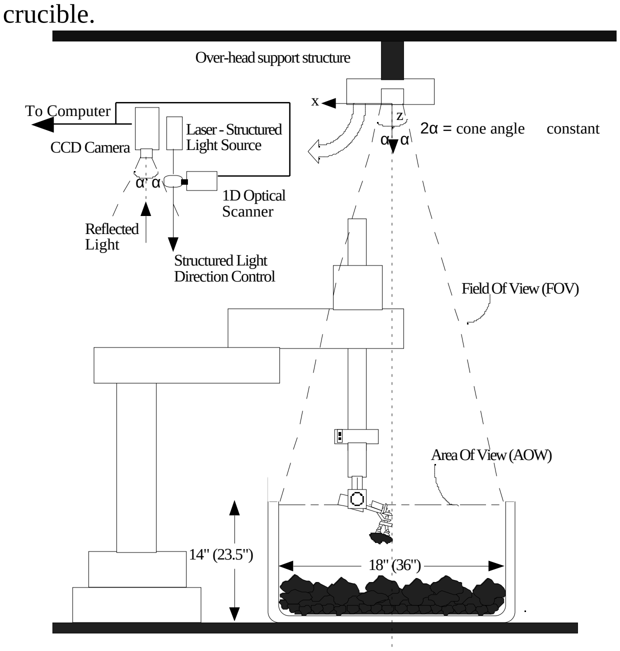

Figure 3: Overhead SGA vision system layout

The SGA optical scanner uses a moving-magnet galvanometer. A moving magnet motor has no saturation torque limit and very little electrical inductance. Thus extremely high torques can be generated very rapidly, an essential feature for systems requiring short step response times. The scanner controller is tuned for the inertial load of its mirror. A capacitive position detector within the scanner provides a differential current position control feedback. A latching digital circuit gives a maximum 16 bits of scanner control, equivalent to 10 μrad resolution.

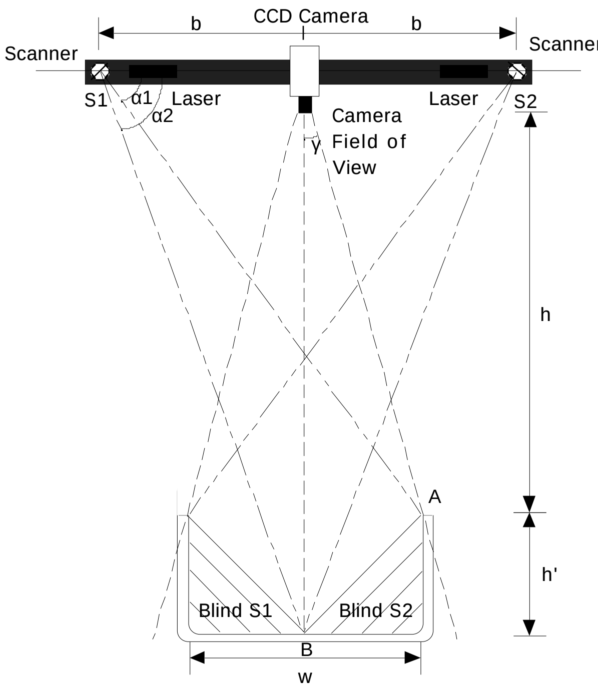

Figure 4: SGA design parameters

Table 1: SGA design parameters

Parameters	Lab Design
H	54 inches
h’	14 inches + crown
W	18 inches
b	36 inches
γ	9.5 degrees
α1	50.3 degrees
α2	63.4 degrees
Camera resolution in pixels	500x500
Z Resolution at A	1.1 mm
Z Resolution at B	2.4 mm
X,Y Resolution at A	0.9 mm
X,Y Resolution at B	1.2 mm

2.3. Nugget Geometry Acquisition (NGA)

The prototype laboratory NGA system is shown in Figure 5. The manipulator carries the nugget over the vision system before it is placed in the crucible. It is scanned in real time as it moves across the camera. This requires careful synchronization of the manipulator motion and the NGA system. The manipulator is required to maintain a constant linear velocity of the nugget across the camera FOV of 3 cm/s based on a 1mm XY resolution, nominal nugget size of 3”x3", and 30 frames/s video rate. The NGA system parameters are summarized in Figure 6 and Table 2.

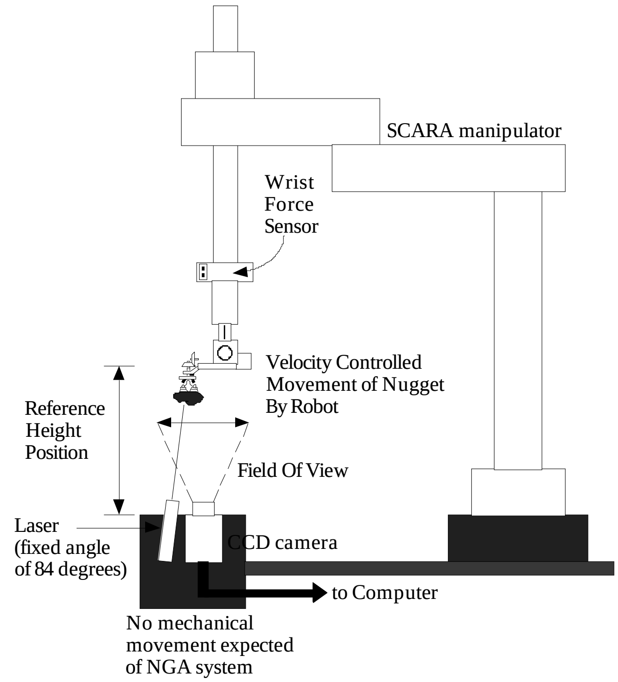

Figure5: NGA System Layout

Table 2: NGA design parameters

Parameters	Lab/Factory Design
h (dist to object – nugget)	10 inches
b	1.7 inches
γ	12 degrees
α	84 degrees
Camera resolution in pixels	1000x1000
Z Resolution	1.03 mm
X,Y Resolution	0.11 mm

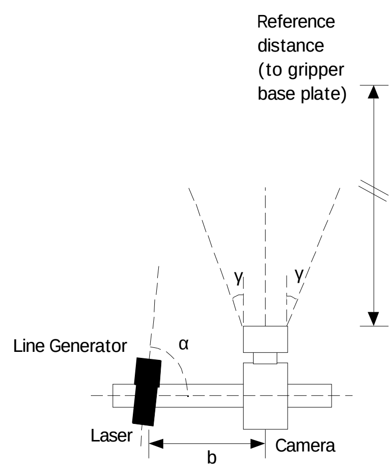

Figure 6: NGA design parameters

3. Calibration

3.1 Intrinsic Camera Calibration

A perfect lens and a detector with perfectly linear characteristics would produce simple trigonometric relationships between the angle of an incoming light ray and the image plane coordinates (u,v) of the light source. In practice imperfections in either of the above elements can result in distortions. The purpose of camera intrinsic calibration is to find and map the errors in image plane coordinates (u,v) due to the non-linearities in lenses, detectors and electronics [10]. These error measurements are use to compensate the measured values to produce accuracy equal to the resolution of the system. Given a known horizontal incident angle γ and vertical incident angle β between the light ray and the principal axis, and a known principal distance f, the "expected" image plane coordinate (u,v) can be calculated. Subtracting these from their actual values gives the error map value.

$u_{expected} = f \,.\, \tan\gamma, \quad v_{expected} = f \,.\, \tan\beta$ (4)
$E_u = u_{expected} - u_{measured} = f \,.\, \tan\gamma - u_{measured}$ (5)
$E_u = v_{expected} - v_{measured} = f \,.\, \tan\beta - v_{measured}$ (6)

This scheme assumes that E_u at γ=0 and E_v at β=0 are 0. For non-ideal lenses the focal length, f, would have to be mapped as an average value given by [10]:

$$f \quad \bar{f} = \frac{1}{n} \sum_{n} \left| \frac{u_{measured}}{\tan\gamma} \right| \qquad (7)$$

Using binary interpolation, an E_u and E_v can be looked up for every (u, v) pair, and compensations made. This error is generally important when system accuracy requirements are at sub-millimeter levels.

3.2 Extrinsic Camera Calibration

The extrinsic variables of the system which have to be predetermined are the effective focal length, f, and the inter-camera laser distance, b. Given an unknown lens focal length, inter camera-laser distance b, and an unknown mounting orthogonality with respect to the ground, it is desired to be able to solve for the unknowns. The geometry shown in Figure 7 yields:

$$l = \frac{g}{\sin\alpha} \qquad (8)$$

$$b = z ? \cot\alpha \qquad (9)$$

$$b = b' - l ? \cos\alpha \qquad (10)$$

$$z^2 + b^2 = r^2 \qquad (11)$$

$$\frac{\sin(\beta - \alpha)}{fh} = \frac{\sin(\pi/2 - \beta)}{r + l} \qquad (12)$$

$$\frac{\sin(\pi - \beta)}{l} = \frac{\sin(\beta - \alpha)}{x} \qquad (13)$$

where g (measurable), α, β (predefined scan angles) and δh (object height) are known. The variable x is defined as the distance between the intersection points of the two incident rays, at angles α and β, with the extended camera lens front nodal plane. This gives six independent equations in six unknowns that can be solved

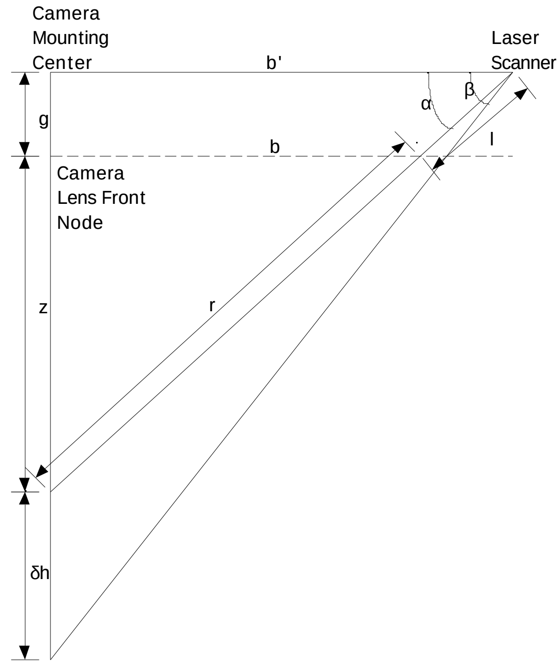

Figure 7: SGA Extrinsic Calibration Geometry

Table. 3 Laboratory NGA extrinsic calibrated parameter values

Optical image size (diameter)	6.477mm
Half angle of view cone	20.6^o
Effective focal length	8.616mm

Table4 Laboratory SGA extrinsic calibrated parameter values

Effective focal length, f	15.8 mm
Inter camera-laser distance, b	890 mm
Front node to mounting center, g	153.03 mm
Object height	101.6 mm
Angle α, β	41.2^o, 44.5^o

In the above it is assumed that the incident angles can be found with the required accuracy.

3.3 Timing Calibration

The final considerations in calibration are timing for the NGA-manipulator interface. At a frame rate of 30 Hz, and a resolution of 1mm, the manipulator is required to travel at 3 cm/s with a maximum allowable error of 0.5mm/s for a scan time of 2.5s. Uncertainties in the video processing rates can lead to larger errors in the position estimation. This error can be resolved by an On-line NGA timing scheme that measures the individual time per frame. Hence, any fluctuations in the frame rate or error in *a priori* knowledge of the frame rate is accounted for.

4. Results

4.1 SGA results

The primary purpose of the SGA system is to provide a map of the nugget field already in the crucible so that the manipulator-packing planner can determine an acceptable location for the next nugget. Figure 8 shows the raw image of a small nugget field, as might be seen in the crucible. Figure 9 shows a plot of the z(x, y) values of this field provided by the SGA system. A 15 KHz data acquisition rate is obtained, given a video rate of 30 frames per second and CCD resolution of 500x500 pixels on a Pentium 166 MHz system. With relatively low cost improvements in both resolution and computational speeds of the SGA hardware the data acquisition rate can easily be substantially increased. The quantitative and independent precise measurement of a nugget field to check the SGA accuracy is difficult. However, estimates of the systems precision indicate that the SGA should meet its required specifications. As discussed below the quantitative evaluation of the accuracy of the NGA can be practically performed.

Figure 8: Nugget field image

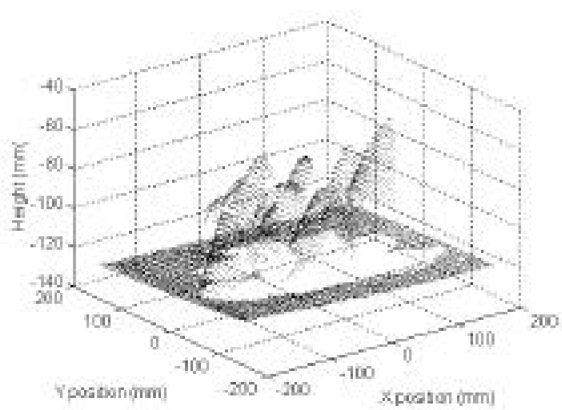

Figure 9: SGA Nugget field mapped profile

4.2 NGA Results:

A number of tests have been performed to evaluate the precision of the NGA prototype system. In the simplest a calibration target consisting of 7 1mm-step profile machined onto a Delrin block was scanned. The average error measured for those tests is ± 0.34mm with σ of 0.12mm. Recall that the accuracy requirement for the NGA system is ±1.0 mm. The system was also evaluated using representative nuggets. Figure 10 shows one such nugget. The profile of this nugget obtained with the NGA system is shown in Figure 11. A section of this profile is shown in Figure 12. Also shown in Figure 12 the error of the NGA profile for this section compared to the profile measured with Coordinate Measuring Machine. The average error is ±0.4mm with σ of 0.2mm. The maximum error seen here is approximately 1mm, which could be partly an artifact of mismatching of the reference data on the mapped profile.

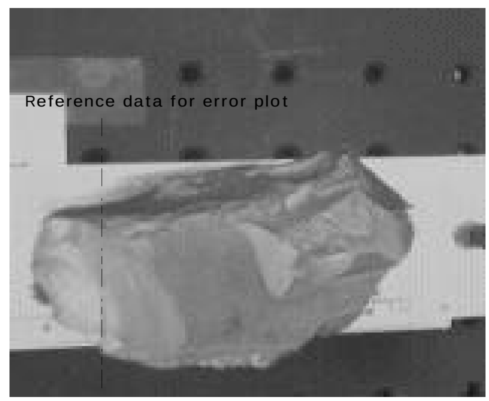

Figure 10: A typical Nugget image

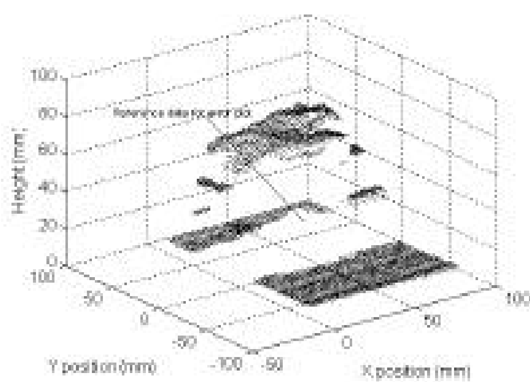

Figure 11: NGA nugget mapped profile

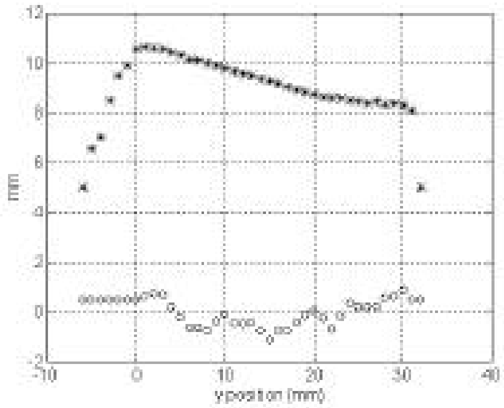

Figure 12: NGA Measured Section Profile (*) profile and NGA Profile Errors Estimated From Coordinate Measuring Machine Data (o)

5. Conclusions

A Robotic System is being developed to automate the crucible packing process of the CZ semiconductor wafer production procedure. A vision system to provide visible surface geometries of individual nuggets and nugget packed in the crucible is a key component of this system

An optical 3-D surface geometry measuring system has been developed based on active laser triangulation. It is found to be within the design constraints of the CZ application. It measures the geometry profile of the individual nuggets being placed and the landscape of the nuggets already in the crucible, with a resolution of 1mm and scanning times of 2.5s and 4.5s respectively, with a nominal data acquisition rate of 15KHz. While this speed can be increased relatively directly by low cost improvements in the basic system hardware, this is sufficient to meet the packing system requirements. This study shows that a practical and effective vision system can be designed to perform important and realistic industrial tasks.

Acknowledgements.

The technical and financial support of this work by Shin-Etsu Handotai Co is acknowledged. Also the technical cooperation of Professor Y. Ohkami and his team at the Tokyo Institute of Technology is much appreciated.

References

1. Antonsson, E.K., *Apparatus for measuring three-dimensional surface geometries.* Application filed January 1989. Patent number 4,957,369, September 1990.
2. Antonsson, E.K. and R.W., Mann, *Automatic 6-D.O.F. kinematic trajectory acquisition and analysis*, ASME Journal of Dynamic Systems, Measurement and Control, 111(1): 31-39, March 1989
3. Besl, P.J., *Active, Optical Range Imaging Sensors*, Machine Vision and Applications, 1(2):127-152, March 1989.
4. Bossiuex, T.A., *Integration of Vision and Robotic Workcell*, Ford Motor Company, 1993, American Institute of Aeronautics and Astronautics Publication, AIAA-94-1186-CP
5. Dietze, W., Keller, W., and Mühlbauer A., “Float-Zone Grown Silicon,” *Crystals, Growth and Applications*, Vol 5. Springer-Verlag, New York, USA 1981, p. 6
6. Dubowsky, S., *Robot Assisted Crucible Charging System - Year II Progress Report*, Shin-Etsu Handotai, Co.., Japan, December 4, 1997.
7. Everett, H.R., *Sensors for Mobile Robots Theory and Applications*, A.K. Peters, Ltd, 1995.
8. Hecht, E., *Optics*, 2nd edition, Addison Wesley, May 1990.
9. Holmes, R., and C., Cummings, *How to choose the proper illumination source,* Techspec--Photonics news and information, Edmund Scientific, Issue 3, Vol 2, Winter 1997-98.
10. Hsueh, W.J., and E.K., Antonsson, *An optoelectronic and photogrammetric 3-D surface geometry acquisition system,* ASME Winter Annual Meeting on Instrumentation and Components for Mechanical Systems, ASME, November 1992, EDRL-TR 92a.
11. Jarvis, R.A., *A perspective on range finding techniques for computer vision,* IEEE Trans, Pattern analysis and Machine Intelligence, PAMI-5(2):122-139, March 1983.
12. Kanade, T., H., Kano, S.Kimura, A.Yoshida, and K.Oda, *Development of a Video-Rate Stereo Machine,* Proceedings of International Robotics and Systems Conference (IROS '95), August 5-9, 1995, Pittsburgh, PA.
13. Leier, A. *Grasping and manipulation of irregular shaped objects with application to the semiconductor industry*. Masters of Science thesis, June 1998, Dept. of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.
14. Luo, R.C., and R.S.Scherp, *3D Object Recognition Using a Mobile Laser Range Finder,* IEEE International Workshop on Intelligent Robots and Systems, IROS '90:673-677.
15. Rosandich, R.G., *Intelligent Visual Inspection*, Chapman and Hall, London, First edition, 1997
16. Rioux, M., *Laser range finder based on synchronized scanners,* Applied Optics 23(21):3837-3844, November 1, 1984.
17. Sujan, V.,*The Sensor based manipulation of irregularly shaped objects with special application to the semiconductor industry,* Masters of Science thesis, June 1998, Dept. of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA.