N90-17910

Use of Anomolous Thermal Imaging Effects for Multi-Mode Systems Control During Crystal Growth

Michael J. Wargo
Massachusetts Institute of Technology
Cambridge, MA 02139

Abstract

Real time image processing techniques, combined with multitasking computational capabilities are used to establish thermal imaging as a multi-mode sensor for systems control during crystal growth. Whereas certain regions of the high temperature scene are presently unusable for quantitative determination of temperature, the anomolous information thus obtained is found to serve as a potentially low noise source of other important systems control output. Using this approach, the light emission/reflection characteristics of the crystal, meniscus and melt system are used to infer the crystal diameter and a linear regression algorithm is employed to determine the local diameter trend. This data is utilized as input for closed loop control of crystal shape. No performance penalty in thermal imaging speed is paid for this added functionality. Approach to secondary (diameter) sensor design and systems control structure is discussed. Preliminary experimental results are presented.

Introduction

Real time thermal imaging has been found to be a powerful tool for passively measuring the effects of applied magnetic fields on the temperature distribution of encapsulated high temperature semiconductor melts during the crystal growth operation. A complete description of the thermal imaging system's design and capabilities is available in [1]. Advanced image processing techniques are employed to reduce or eliminate temporal as well as spatial high frequency noise from the image. In this way spurious perturbations, such as bubbles entrained within the encapsulating liquid glass layer, do not effect the quantitative determination of the local temperature distribution. (See figures 1 and 2 for photographic and schematic descriptions of the thermal imaging process and appartatus.) However, certain attributes of the optical path related to the geometry of the high temperature scene introduce anomolous light intensity information which is not directly related to the temperature at that position in the image.

A typical example of this behavior is illustrated in figure 1 reproduced from [1]. The horizontal line across the 512 x 512 digitized image (8 bit, 256 gray level) is user input using a mouse-type pointing device. In this case, the line was selected to cross the encapsulated melt as well as the meniscus region located at the edge of the growing crystal. The light intensity data (directly related to the temperature of the melt) is read from this line and dynamically superimposed on the image. The information has been subjected to a linear convolution to reduce the effects of high frequency spatial noise. The peaks in optical intensity associated with the meniscus region (at the edge of the crystal) are unrelated to the local temperature since the temperature of the melt in contact with the crystal must be at the melting point of the material being solidified (in this case, GaAs). This behavior is currently interpreted as a measure of the radiation from the hot crucible walls which is reflected by the curved meniscus (non-normal to the CCD imaging camera, see figure 3 for details). However, this anomolous thermal information provides for an indirect measurement of the evolving crystal shape since the distance (in pixels, 0.3 mm/pixel) between peaks is proportional to the diameter. This difference data is used as input to a closed loop proportional controller for control of the crystal diameter during growth. The system input which is changed by the proportional controller is the heater temperature ramp rate. The temperature of the heater is monitored by a thermocouple situated in close proximity to an element of the heater and controlled using a digital PI (proportional/integral) controller. (See section on **Control Algorithm Development and Experimental Results** and figure 8.)

Experimental Approach

A conventional silicon puller (Hamco CG-800) was modified for the low pressure growth of GaAs by LEC (Liquid Encapsulated Czochralski) pulling. A thermal imaging system based on real time image processing techniques has been developed and is operational on the puller. All control inputs (motor rates, temperature control etc.) are activated via digital to analog conversion (D/A) of operator chosen or predetermined feedforward trajectory values (figure 4).

The systems architecture of the thermal imaging system is given in figure 2, from [1]. The melt is viewed in near normal incidence by a charge coupled device (CCD, 512 x 512 pixels) camera. The resulting monochromatic image (due to a 1 nm wide filter centered on 633 nm) is digitized (8 bit / pixel) and processed using a pipelined pixel processor operating at an effective 40 million operations per second. The images are held in digital storage units which appear as extended dual ported memory on the bus of the main CPU. In this way image data is accessed in parallel by both the vision engine (real time image processing hardware and software) and CPU with its related floating point and array processors, permitting significant filtering of both spatial and temporal noise while maintaining real time (30 frames per second) imaging performance. The diameter inference is obtained as described above. A significant advantage to this measurement of crystal diameter is that it is insensitive to even a substantial degredation of the optical path (e.g. 'fogging' of the windows by evaporated arsenic). This is due to the measurement of the position of the peaks in intensity not the value of the peak intensity.

Control Algorithm Development and Experimental Results.

Initial experiments were carried out using a pure diameter error signal (Diameter[desired] – Diameter[measured]), with no image filtering, for feedback to the heater temperature using a conventional proportional/integral (PI) digital control algorithm. This approach to active diameter control gave results during growth which indicated two fundamental limitations. First, without temporal and spatial filtering of the image the diameter measurement signal contained fluctuations associated with perturbations caused by the presence of entrained bubbles in the liquid encapsulant which caused the temperature controller to change the diameter in a monotonic mode, i.e. the diameter either was reduced to zero (The crystal pulled off.) or it increased to the crucible wall (The melt surface froze.). Second and related, this approach did not take into account the dynamic changes in heater temperature required during pulling to respond to the batch nature of the process: the process is transient.

The effect of temporal filtering in obtaining a reduced noise representation of crystal diameter is shown in figures 5, 6 and 7. The thermal imaging of a crystal growth experiment was archived on a professional video tape recorder (Sony BVU–800) and used post experiment to determine the crystal diameter with and without the use of a temporal averaging alogrithm. Diameter sensing in figure 5 employed no digital filtering (temporal or spatial) while the data in figure 6 was obtained with the application of a temporal filtering algorithm with a 4 second time constant. (120 images [4 s x 30 images/s] were averaged.) The post growth measurement of the actual crystal diameter is given in figure 7. Further optimization of this filtering procedure is in progress.

The current control algorithm is a combination of feedforward and feedback components (figure 8). During growth, the diameter is measured (as described above) from images processed with both temporal and spatial filters. In five minute increments the latest diameter data (taken at 10 s intervals) is analyzed by linear regression to obtain the local diameter trend. This is compared with a set point which is no longer the absolute diameter but rather a pre-selected (and changeable) diameter slope (diameter as a function of time or distance grown). Any deviation of the measured diameter slope from the setpoint diameter slope is used as an error signal to modify using a simple proportional controller, not the absolute heater temperature, but the rate of temperature reduction of the heater (the heater temperature trajectory). The error and new heater trajectories are calculated as follows:

error = diameter slope [desired] − diameter slope [measured] [eq. 1]

new heater temperature trajectory = old trajectory − P * error [eq. 2]

Where P = proportional constant for controller.

This approach to automatic diameter control was used during low pressure LEC pulling of GaAs. The results are shown in figure 9. The ADC algorithm was initiated 5 cm following seeding. The setpoint (diameter slope) was initialized at 6 mm/hr. With the rate of pulling set at 1.3 cm /hr, the resulting diameter rate setpoint was 0.46 mm / cm of growth. The superposition of this slope on the crystal shape is in qualitative agreement with the trend in diameter as grown. The cyclic nature of the response indicates that the sensor did register the changes in diameter and the controller did respond in such a way so as to reverse adverse trends. The amplitude of these changes indicate the lack of controller tuning and the effects of residual diameter signal noise. It is important to note that control action was not characterized by a limit cycle response. The controller was not responding alternately between its upper and lower limits. Work is in progress in both areas.

Discussion

Closed loop diameter control during LP–LEC pulling of GaAs using thermal imaging based diameter sensing has been accomplished. A simple proportional controller is used to maintain a diameter slope setpoint by modifying the heater temperature trajectory. Noise in the diameter signal associated with video transmission noise and temporal perturbations within the high temperature scene (e.g. bubbles) have been reduced by real time spatial and temporal averaging algorithms. Residual noise in the diameter signal (for example, from 'stationary' bubbles) still causes perturbations in the control action. The solution to this problem will be sought by sensing the diameter from multiple regions of the thermal image (at various angles around the crystal) and using the 'best' data as determined from comparison with previously established good data values. An optimized value of the proportional constant will be determined both from feedforward response of diameter to heater temperature trajectory as well as from experimental experience.

Acknowledgements

The author is indebted to the Defense Advanced Research Projects Agency and the National Aeronautics and Space Administration for their support of this work. The stimulating technical discussions with Prof. August F. Witt, Dr. Douglas J. Carlson, Prof. S. Motakef and Prof. M. Gevelber contributed significantly to this effort.

Bibliography

1.) M.J. Wargo, "Real Time Thermal Imaging of High Temperature Semiconductor Melts", NASA Conference Publication 2503, Proceedings of a workshop held at NASA Headquarters Washington, D.C., April 30 – May 1, 1987, Published 1988, p. 384.

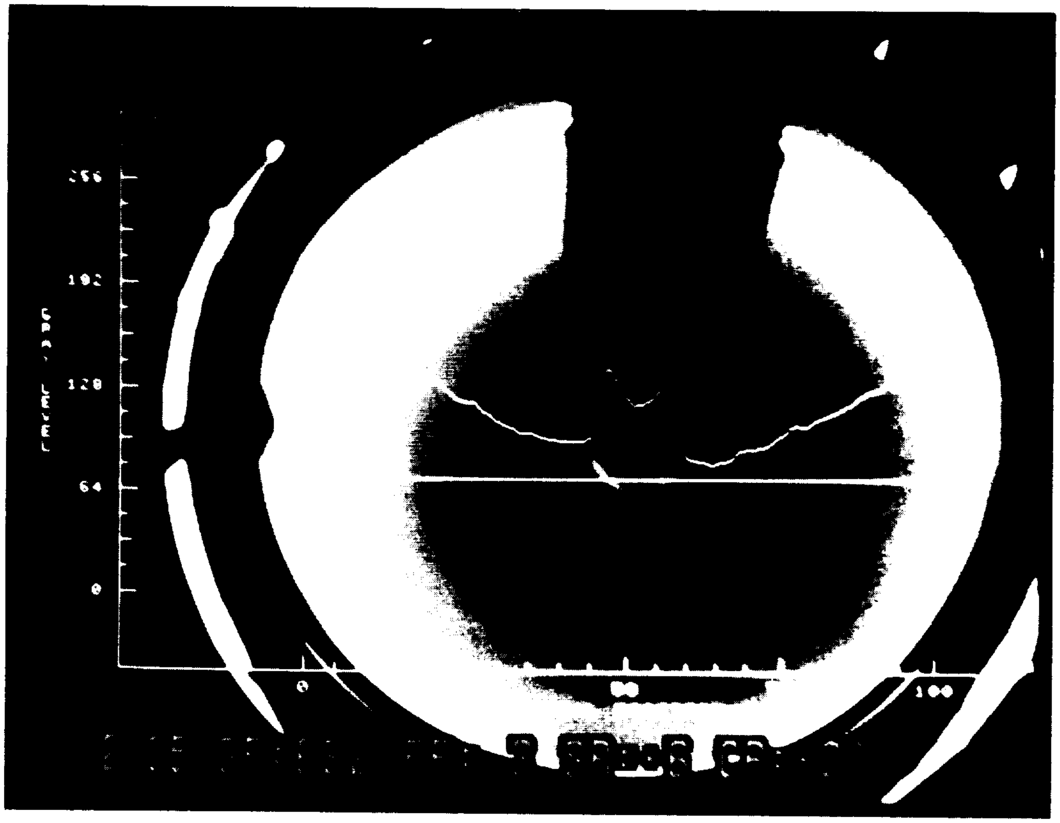

Figure 1. From [1]. Thermal image acquired during LEC growth of GaAs. The anomalous behavior of the measured thermal image in the meniscus region is used to infer the evolving shape (diameter) of the growing crystal.

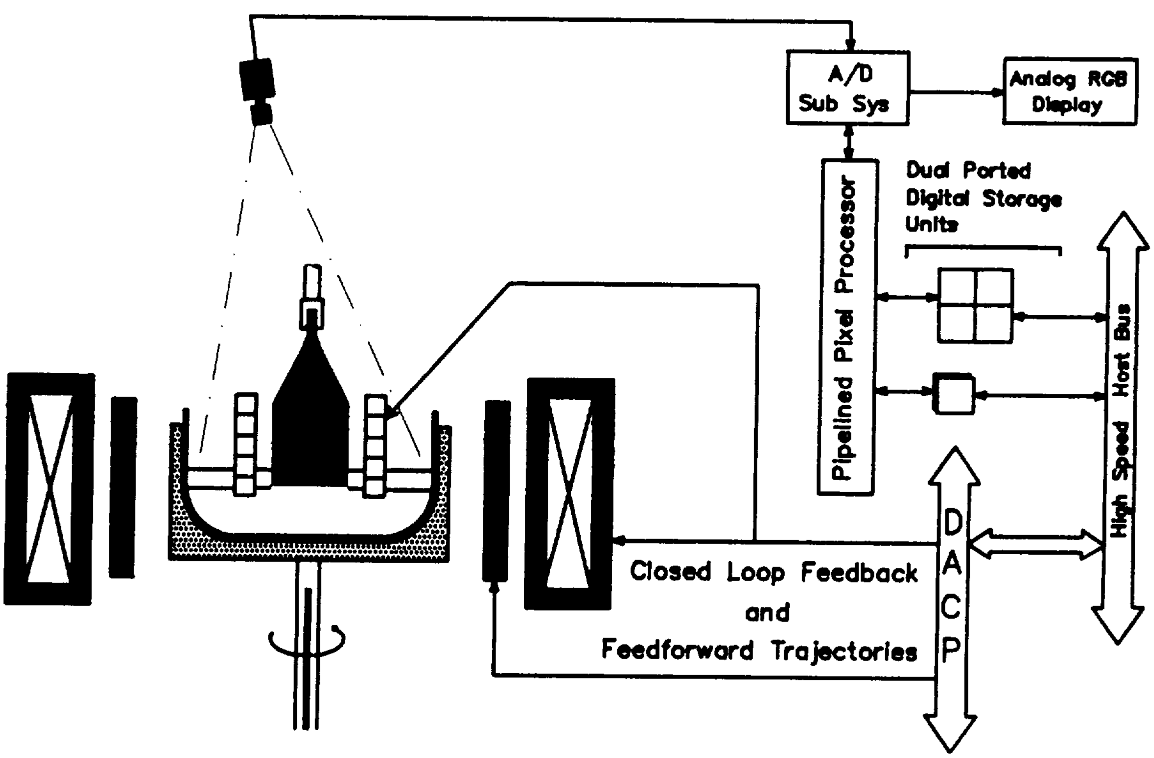

Figure 2. From [1]. Thermal imaging architecture and control structure for LEC growth of GaAs. Details can be found in [1].

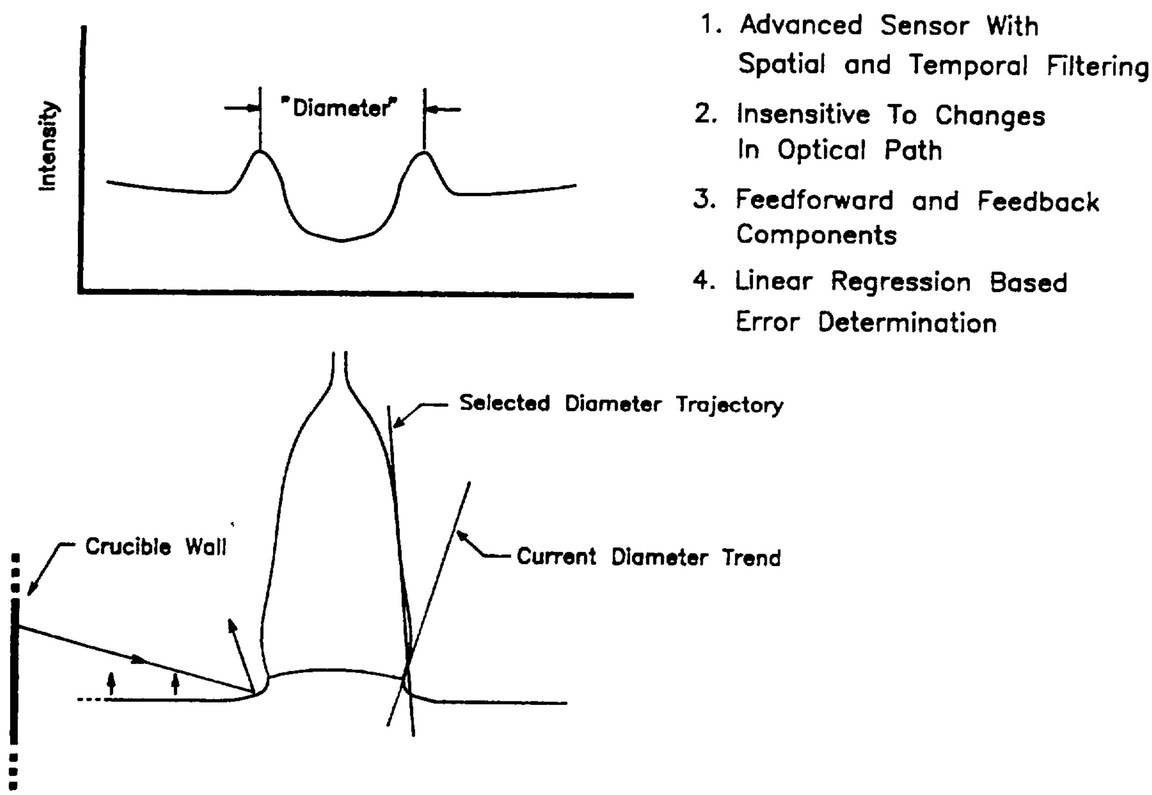

Figure 3. Inference of the crystal diameter during growth is made from anomolous thermal imaging information in the region of the meniscus formed between the crystal in contact with its melt. The large peaks in intensity measured in this area are currently interpreted as due to the radiation emitted from the high temperature crucible walls which is subsequently reflected from the curved surface of the meniscus.

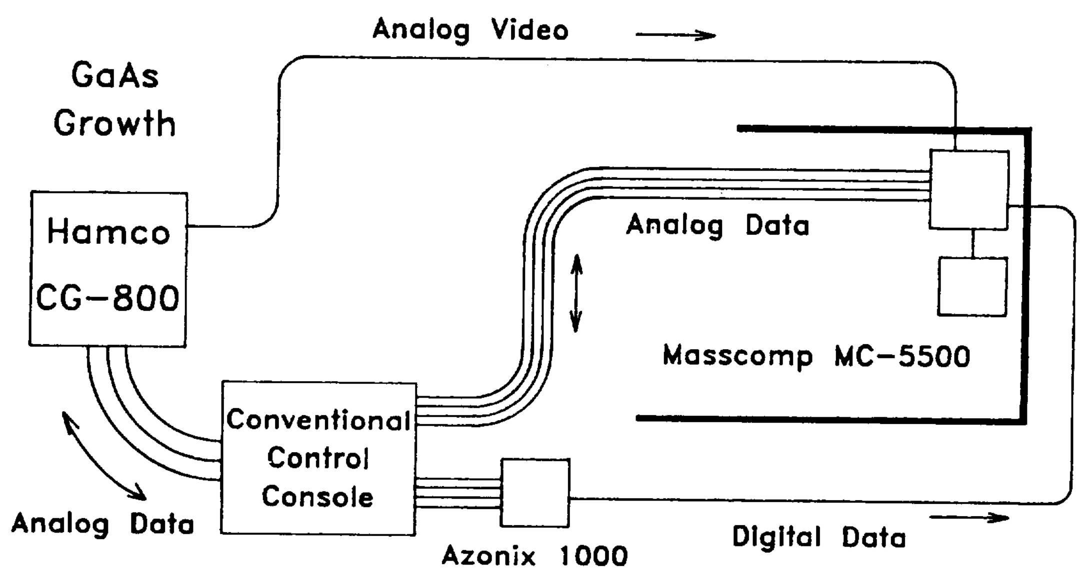

Figure 4. Data management for thermal imaging and growth control. Analog sensing and control information is exchanged with the growth system by A/D and D/A conversion within the Masscomp MC-5500. The analog video information (for thermal imaging and diameter inference) is digitized by the analog front end of the real time vision engine incorporated in the Masscomp MC-5500. (See [1] for details.) The Azonix 1000 provides 18 bit resolution direct digitization of the thermocouple sensor used to determine heater temperature.

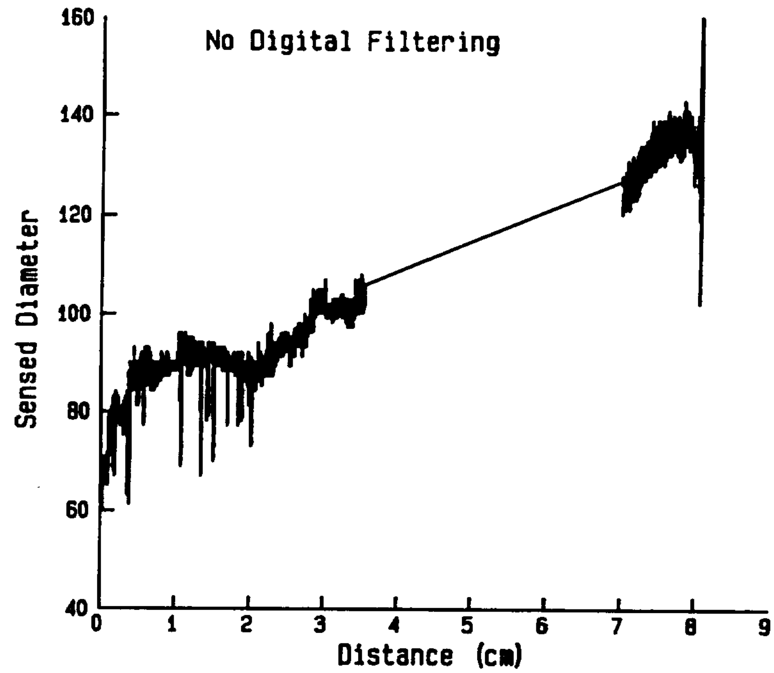

Figure 5. Crystal diameter (in pixels) inferred from archived thermal imaging information. No image processing algorithms (temporal or spatial) were applied to the video information.

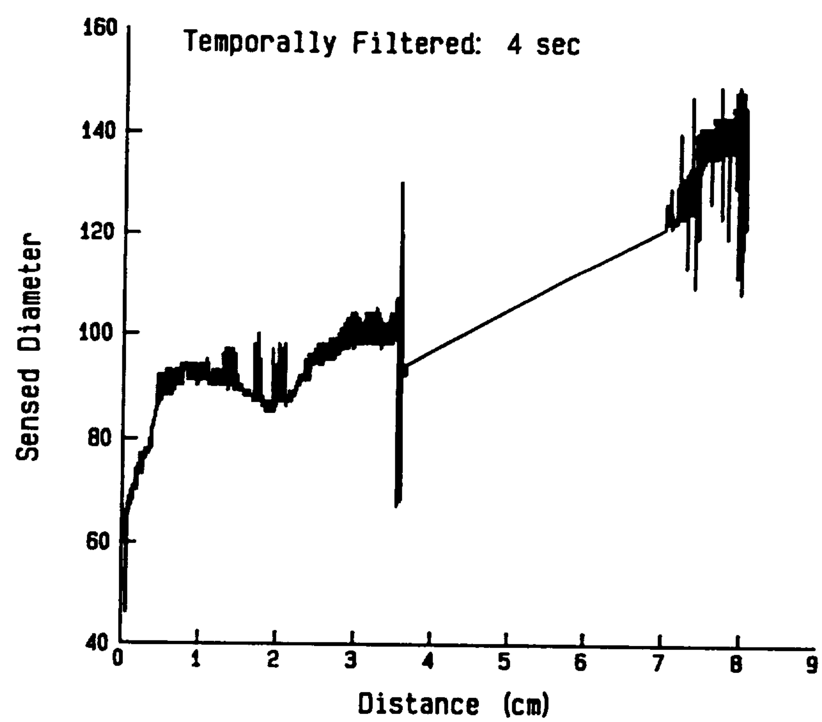

Figure 6. Crystal diameter (in pixels) inferred from archived thermal imaging information. A temporal averaging algorithm was used to reduce the effect of perturbations (e.g. entrained bubbles in the encapsulant). See text.

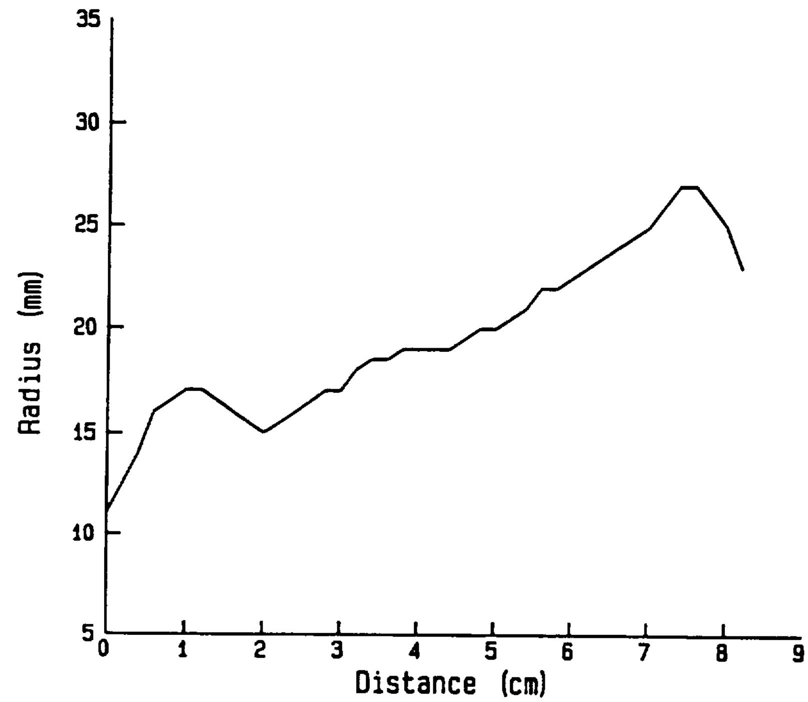

Figure 7. Actual measured diameter of the crystal analyzed in figures 5 and 6.

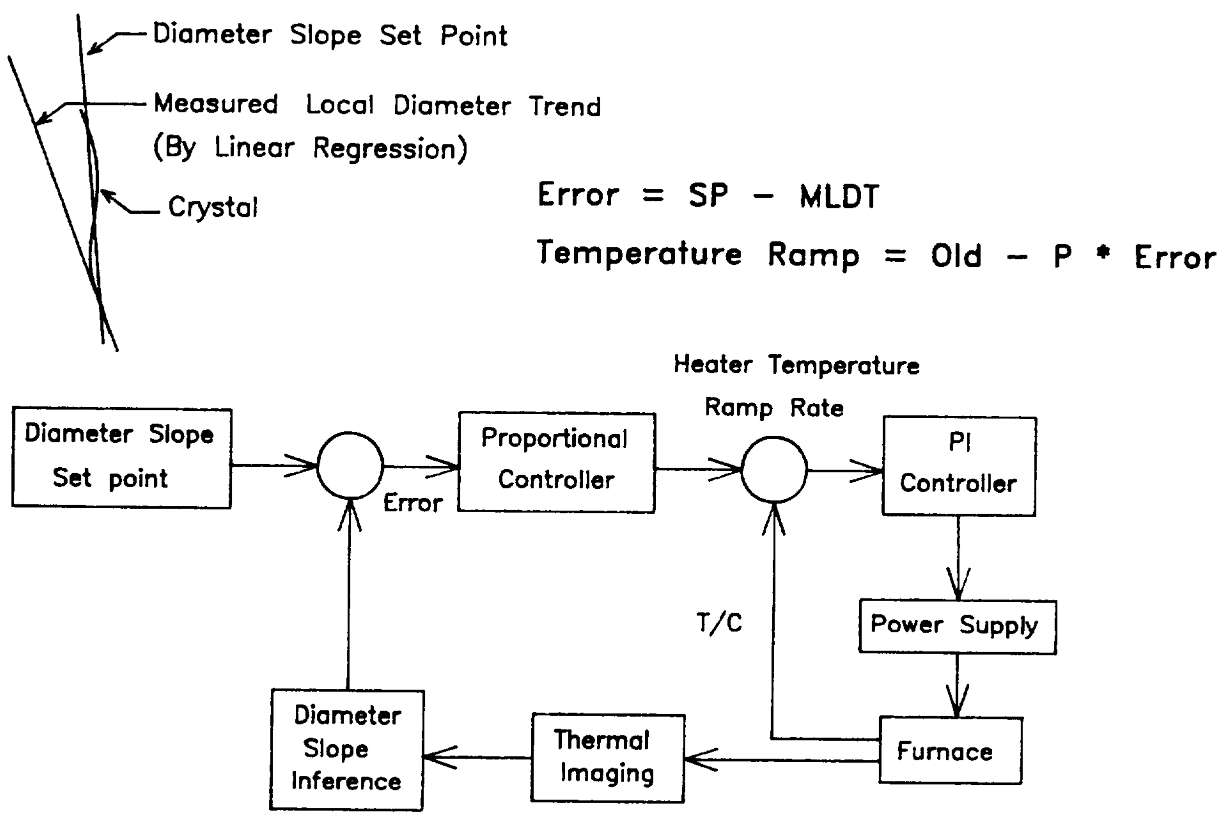

Figure 8. Control structure and algorithm used for closed loop control of crystal shape using a diameter signal inferred from anomolous thermal imaging information.

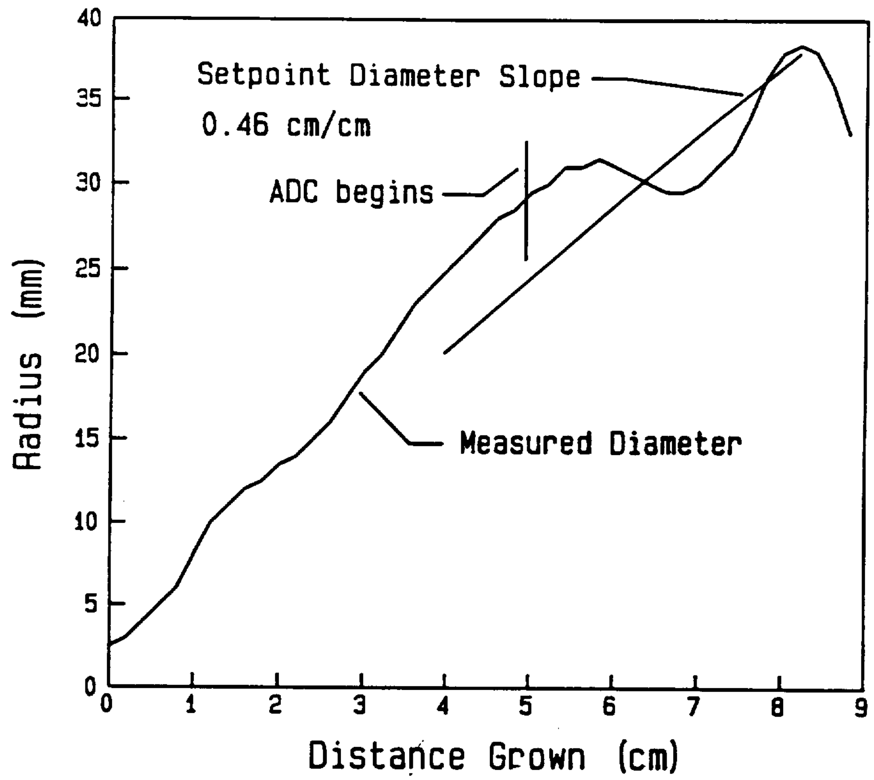

Figure 9. Preliminary experimental results of closed loop control action based on the structure and algorithm given in figure 8. See text for details.