THE DESIGN OF AN AUTOMATED POWDER DEPOSITION SYSTEM FOR A THREE-DIMENSIONAL PRINTING MACHINE

by

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Submitted to the Department of Mechanical Engineering on May 10, 1991 in partial fulfillment of the requirements for the degree of Bachelor of Science

ABSTRACT

Three Dimensional Printing is a process for the rapid manufacture of tooling and functional prototypes from a CAD model. Layers of a granular powder are selectively bound by inkjet printing a binder material onto each layer. An x-y positioning system is used to control the raster scan of a modulated nozzle over a powder bed. The unbound powder is then removed, leaving the printed three-dimensional part. The primary applications of the process are the manufacture of ceramic shells and cores for metal casting and the fabrication of ceramic preforms for metal matrix composite infiltration. Three dimensional printing may be used in the production of ceramic , metal, and metal-ceramic composite parts.

The quality of the surface finish and accuracy of the part dimensions are dependent on the thickness and density of the layers. To maintain uniform and precise powder layers the powder deposition process must be repeatable. The automated spreading system developed to meet these requirements drops and spreads fixed volumes of powder before the printing of each layer. Many methods of dispensing precise amounts of powder were investigated; the process of spreading the powder with a cylindrical rod rotated counter to its traverse was found to be easily repeatable. The powder deposition system employs a paddle-wheel feeder to drop the necessary volume of powder and a counter-rotated, fixed height, vibrating rod which traverses the powder bed and spreads the powder.

Thesis Supervisor: Dr. Emanuel Sachs

Title: Rockwell International Associate Professor of Mechanical Engineering

Dedication

This Bachelors thesis is dedicated to Gwendolyn and Gerald Pruitt, otherwise known as Mom and Dad. Thanks for all your love and support through the years. I especially want to thank you, Dad, for ali your encouragement and insight into how to survive an MIT degree and still have fun.

Acknowledgements

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I would like to thank everyone on the Three Dimensional Project, a.k.a. the Muppet Lab; it's been a great learning experience and a lot of fun working with all of you. Working with you all, I saw MIT humor at its best if not its worst. Thank you Dave Brancazio for all your help and humor, including *your* looney idea to build a 2.70 placebo. Of course, I cannot acknowledge lab humor without acknowledging Jim Bredt; thanks for keeping it light.

Fred Cote, I couldn't graduate in good conscience without acknowledging the tremendous support you've given me. Thanks for always taking the time to show me how to to do it *right*. (And how to do it quick when it came down to that too!)

Kevin Spratt, thanks for always being our reality check--I think, but seriously, I'll need a beer after this one!

And many deserved thanks go to my family and friends, Lisa and Cal, Jackie, and especially Mike for putting up with me and helping me through the good and bad.

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1. Introduction

1.1 Motivation

The growing concerns of industry are productivity and competitiveness; impediments to productivity and competitiveness are the lead times and costs of tooling, particularly at the prototype stage. Rapid prototyping of parts and tooling drastically reduces the investment level currently involved in the manufacture of prototype tooling, the largest cost and time contributor of most manufacturing processes. The production of prototype designs facilitates the design process by giving immediate feedback to the designer in terms of aesthetics, dimensions, and fit.

Through the rapid manufacture of tooling, Three Dimensional Printing also targets the critical problems of lead times on tooling, time to market and cost of tooling. Cores and shells for casting and molds for forging or injection molding could be directly printed with no special tooling involved. By reducing the time to market for new products and allowing the flexible manufacture of products in small quantities, Three Dimensional Printing facilitates greater competitiveness and higher productivity.

1.2 The Three Dimensional Printing Process

Three Dimensional Printing allows for rapid prototyping of components from Computer Aided Design Software (CAD) Models. The present research is directed at the manufacture of tooling for casting by printing the ceramic shells and cores directly. The process may also be applied in the three-dimensional printing of CAD prototypes or the manufacture of one of a kind items. The Three Dimensional Printing process selectively binds layers of a loose granular material by inkjet printing two-dimensional patterns of a liquid binder. The binder is delivered by the raster scan of a modulated inkjet nozzle. Currently, the materials used are alumina powder and a colloidal silica binder. The use of similar ceramic materials is also possible; experimentation with parts printed with metal powders and polymer binders is also being done.

The process of Three Dimensional Printing begins with the deposition of a base layer of powder over a ceramic substrate. The first layer of the part is selectively bound by inkjet printing a two-dimensional pattern of binder on the powder. The printed layer is then lowered a specified distance (typically 0.007") by dropping the piston which supports the part. A line of powder deposited along one piston wall is spread across the piston by a counter-rotating cylindrical rod. The counter-rotating rod creates a uniform layer while transmitting very little shear forces from the flowing powder to the printed layer beneath. Previous experimentation has shown that vibrating the rod axially increases the densification of the powder layer. The next two-dimensional pattern of binder is printed on the new powder layer. This process of stacking and joining two-dimensional layers is continued until the three-dimensional part is complete. The volume of powder, bound and unbound, is then removed and fired at a temperature of 800°C. The formulation of the of printed part in a powder bed allows the printing of overhangs and non-enclosed voids as well; unbound powder surrounds the printed part and gives support until the part is fired and set, the unbound powder is then removed. The sequence of printing operations is shown in Figure 1.

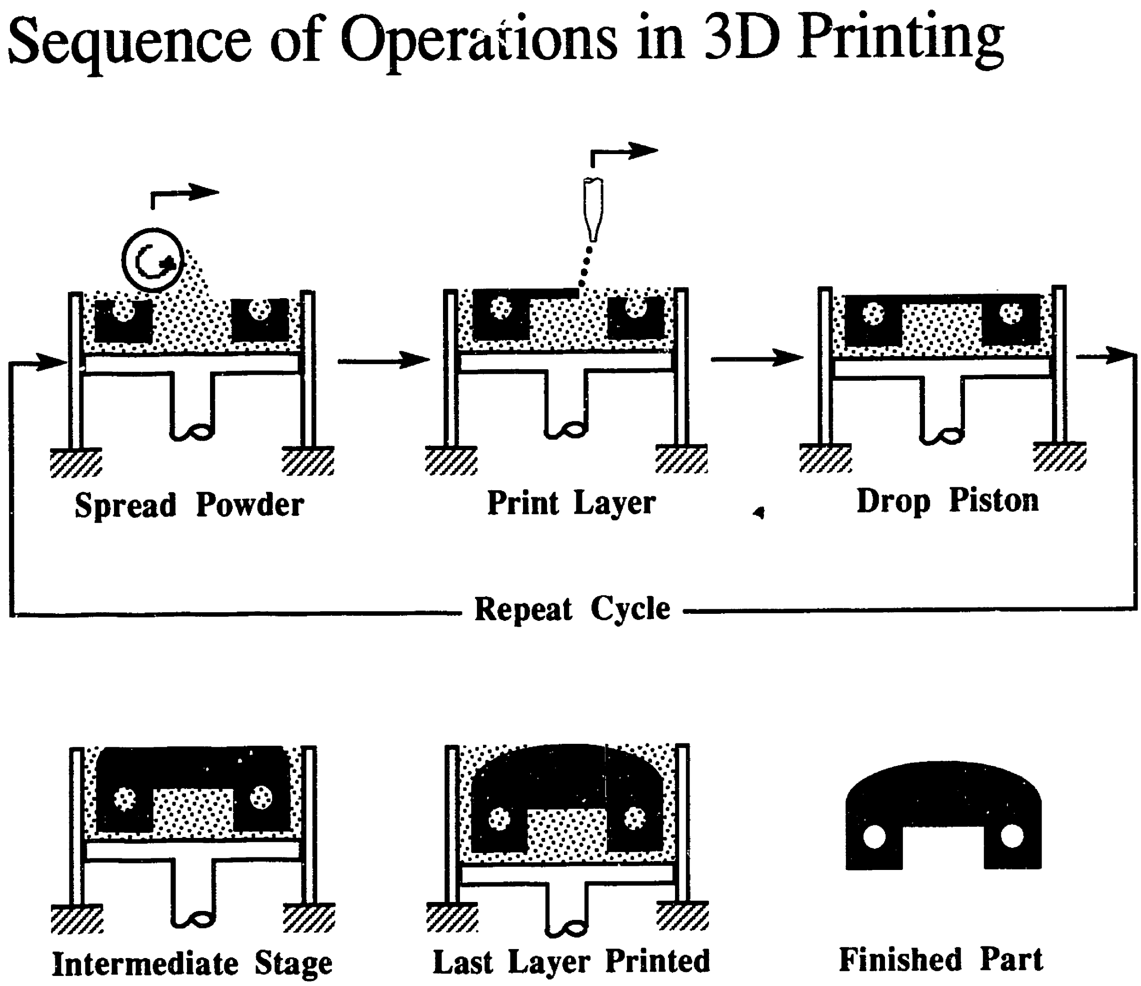


Figure 1. Sequence of operations in the Three Dimensional Printing Process.

1.3 Automation of Powder Deposition

Manually spreading the powder adds time and uncertainty to the printing process. The manual method of powder deposition is to drop the piston by inputting a specified distance to the computer, to deposit a sufficient quantity of powder on the piston wall, and to spread the powder as uniformly as possible by counter-rotating the rod as it traverses the powder bed. The deficiencies of manual deposition are numerous. The deposition of powder from person to person is tremendously inconsistent. The volume of powder that gets packed into each layer varies with each operator; some users might spread the amount of powder on the wall until most all of it is compacted into the layer, while others use just enough powder to fill the layer. Some layers are spread by one pass of the counter-rotating rod; others by a forward and a back pass. The angular velocity of the rod and downward force on the rod varies not only from person to person but also part to part and layer to layer. Even the most proficient operator could not reproduce the spreading process precisely. Aside from the inherent inconsistencies of manual spreading, the time to be saved by automating the spreading process is enormous. The manual spreading of each layer is very tedious and time-consuming. Manual powder spreading requires a full-time operator of the printing machine. To facilitate the production of parts and allow the machine to be left unattended while in operation, the development of a reliable, repeatable powder deposition system was required.

2. Powder Deposition

2.1 Methods of Powder Distribution

Several methods for dispensing precise amounts of powder are available for dry powders. Most deposition processes require that the powder flow easily in the presence of a small shear force, powders with a grain size of approximately 50 microns or greater typically exhibit this behavior. The flow of finer particles is dominated by interparticle forces which produce aggregates of particles and prevent their free motion. Very fine particles require the presence of a liquid vehicle. Chemical additives are used to augment the interparticulate forces to insure that they are repulsive. These dispersants are common in paints and ceramic tape casting formulations [Patton 1979].

Feeders for fixed flow-rate or fixed volume applications are available. Particles can be dispensed in a dry bulk state from a hopper; flow of powder from the storage hopper must be induced by the use of vibration or agitation. Dominant types of industrial particle feeders in use are vibratory feeders, screw feeders, and belt conveyers. A belt conveyer requires a prefeed staging of the powder and is generally applicable only to large grain substances such as sand. Vibratory feeders are commercially available for large and small scale uses; those feeders developed for use by the pharmaceutical industry typically dispense volumes of powder in gram-fraction quantities, on the order of the Three Dimensional Printing application. Vibratory feeders shear powder from the entire cross-section of a flat-bottomed hopper. Commercially available feeders drop powder in mounds; to create a uniform line of powder, the feeder or receiving surface would need to traverse the length of the line of powder. Vibratory feeders work on a controlled flow rate principle, more precise monitoring through a loss-in-weight controller is possible. Flow rate of a granular substance is related to the angle of the vibratory plates and the powder handling characteristics; the vibratory blade dimensions and angle are suited to the particular handling characteristics of a powder, such that when the vibrations cease, the powder flow stops under the action of the angle of repose of the material [Solids Flow Control]. The angle of the vibratory chutes or blades is specific to a particular powder and the powder handling characteristics of powders are extremely sensitive to changes in humidity and grain size [Solids Flow Control and Jonkers, 1983].

Precision of a vibratory feeder is a function of speed. Speed is controlled by the vibration rate and the size of the train of powder in the trough, a heavy train of powder provides rapid delivery [Osborne, 1972]. The requirements of a feeder may be better predicted by knowing the characteristics of the powders to be used. With the proper equipment, flow properties such as the required translational shear and bulk yield behavior, the influence of moisture content and time-consolidation on the flow behavior, the granular friction properties, as well as bulk density and permeability may be determined experimentally [Jonkers, 1983].

Screw feeders shear powder front to back and require that the supply hopper be tapered since only the surfaces in contact with the screw experience shear. The powder flows in the hopper due to the agitation of the screw and powder in the screw is sheared forward by forced volume displacement. Any type of system employing a component to agitate the powder is classified as a screw feeder. Screw feeders work well for a large range of particle sizes and the action is independent of most flow characteristics. Wear and of the agitation device in the screw feeders is a limiting factor in its long-term use and maintenance. Abrasive powders, such as alumina and other ceramic powders, accelerate the wear of the moving parts; dispensing corrosive particles or different powders also presents problems of contamination and increased cleaning and maintenance of the feeder. Particle aggregates formed in the presence of excess moisture are a problem in screw feeders, vibratory feeders, and belt feeders which are not operating in a controlled environment. Finer particles also pose special distribution problems. While finer particles can be moved by agitation, airborne particulates become a problem; however, a covered or sealed system limits the travel of the particulates.

2.2 Requirements of Powder Layers

The thickness and density of the powder layers determines the accuracy of the part dimensions and quality of the surface finish. To achieve accurate dimensions, the layers must be uniform in density and flatness as well as precise; thus, the layers must be generated by a repeatable and accurate process. The thickness of the layers is determined by the relative position of the piston and powder bed to the piston walls and spreading mechanism. Misalignment or variable height of the spreading mechanism can create uneven layers. The density of the layers is a function of particle size and the material packing. A process which can achieve maximum densification for a given particle size is optimal.

Denser powder packing allows denser parts and greater part strength. Density control could possibly be achieved using controlled vibration, varied volumes of deposited powder, or variable rod rotation and traverse speeds. Vibration of the spreader-rod has been observed to increase part density by as much as 30% more than the density achieved by spreading alone; this densification occurs through consolidation of the individual layers.

Density control, as well as binder per unit volume, controlled through binder flow rate, would allow custom tailoring of shells and cores to particular casting and leeching processes.

A finer particle size also allows closer tolerances than those achieved with larger particle sizes; however, fine particles pose special distribution problems. Very fine particles succumb easily to static electricity as well as cohesive and adhesive forces. Very fine particles can only be effectively distributed by using fluid vehicles, gaseous or liquid, or preformed powder layers or strips. However, uniformity and consistency of the layers is difficult to achieve with these methods.

3. Design of a Powder Deposition System

3.1 Automation of the Powder Spreading Process

In the developmental stage of the three dimensional printing process much experimentation is still being conducted in the areas of powder selection, metals and ceramics, and the effects of grain size. To allow diverse powder experimentation and to limit complexity, the automated spreading process mimics the manual process. The system employs a paddle wheel which works on the volume displacement principle of a screw feeder. The three inch wide paddles delivers a stream of powder down a chute. The deposition of powder is shown in Figure 2. The volume of powder required for one part is stored in a small tapered hopper. The flow of powder from the hopper is agitation induced as in a screw feeder; as such, the paddle-wheel hopper is subject to the same concerns of wear and contamination.

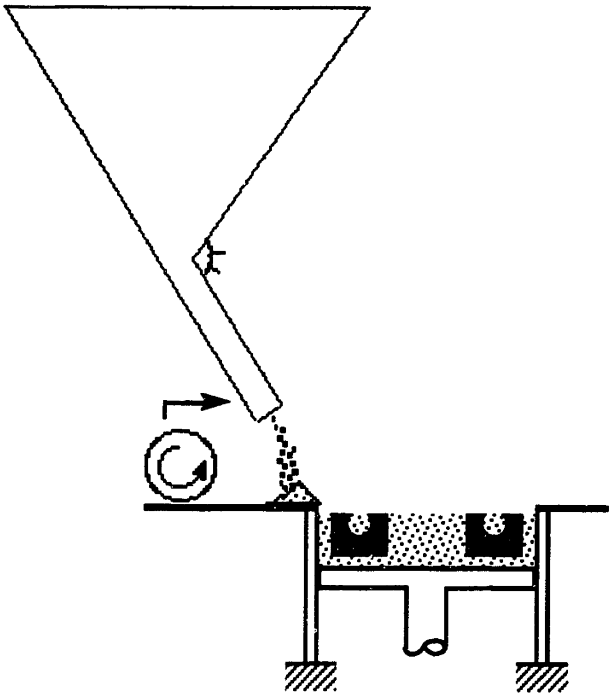


Figure 2. Powder Deposition

With the paddle as an agitator, the hopper must be tapered. At angles between 30° and 45°, the flow of agitated alumina powder with a particle size of 45 microns has an almost parabolic front and uniform thickness. The powder flow resembles two-dimensional Poiselle flow with the maximum powder flow centered in the middle of the chute as shown in Figure 3. The line of powder deposited at the base of the chute is highest in the middle and its volume is distributed along the length of the piston edge.

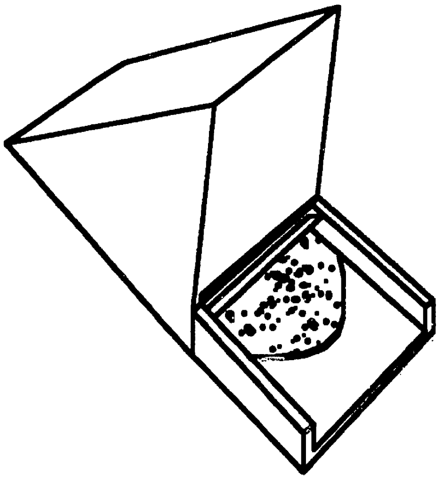


Figure 3. Agitated Flow of Powder from the Powder Hopper

A counter-rotating cylindrical rod traverses the powder bed and shears the powder up and away from the printed layer beneath as it pushes the powder ahead. As the roller bar traverses the piston bed, the powder flows parallel to the bar as well as ahead of it. Excess powder falls into a catcher over the side and end walls. Spreading a line of powder which is highest in the middle allows this sideways flow to occur with less wasted powder falling off the sidewalls.

3.2.1 Control of the Powder Deposition Process: Initial Approach

The initial approach to automating the powder distribution was to develop an independent system which was triggered by the computer when the printing of each layer was complete. Several changes have been incorporated to this first system but the underlying principles remain unaltered. The prototype system used minimum computer output ports and CPU time. Limit and optical switches were rejected based on the powder environment and space constraints. Instead, a series of pulses from one computer output port were used to control the two motors driving a simple cantilevered counter-rotating rod and a paddle-agitated powder hopper. The rotation of the rod was driven by a DC motor, the transverse action of the rod over the piston is piggy-backed onto the x-axis, or slow axis, of the printhead motion controller; the x-axis of the machine is driven by a lead screw stepper motor controlled by the DCI controller. The computer pulses were generated when the controller was at known reference positions. Both supports of the cantilevered rod were independently pinned to let the rod to ride on the piston walls and allow its weight to maintain its horizontal alignment. However, the wear caused by the rotating rod and abrasive powders was undesirable on the squared piston walls. The independent control circuit also added more time to the process as the computer program allowed a fixed time for sequence to end before beginning next layer.

3.2.2 Control of the Powder Deposition Process: Present System

The independent digital circuit did not prove robust. A missed signal due to noise or jostling put the whole powder deposition cycle out of phase with the print cycle. A control card was added to the computer to allow additional outputs for the process control. The DCI controller interface to the computer allows the computer to generate control signals for the powder deposition cycle based on the x-y position. Direct signal generation by the computer has been much more reliable than independent signal processing.

The printer and powder distribution subscribe to the timing diagram in Figure 4. Three control card outputs are implemented; one signal switches the rod rotation, one signal switches the rod vibration, and one switches the powder feeder on. The controller signals switch the two 24V DC drive motors through Opto-22® optically coupled DC relays in line with motors and power supplies. The computer can source up to 16mA while the relays draw a nominal current of 12mA. To guard against overload, duplicate signals are carried on separate channels for the rod vibration and rotation.

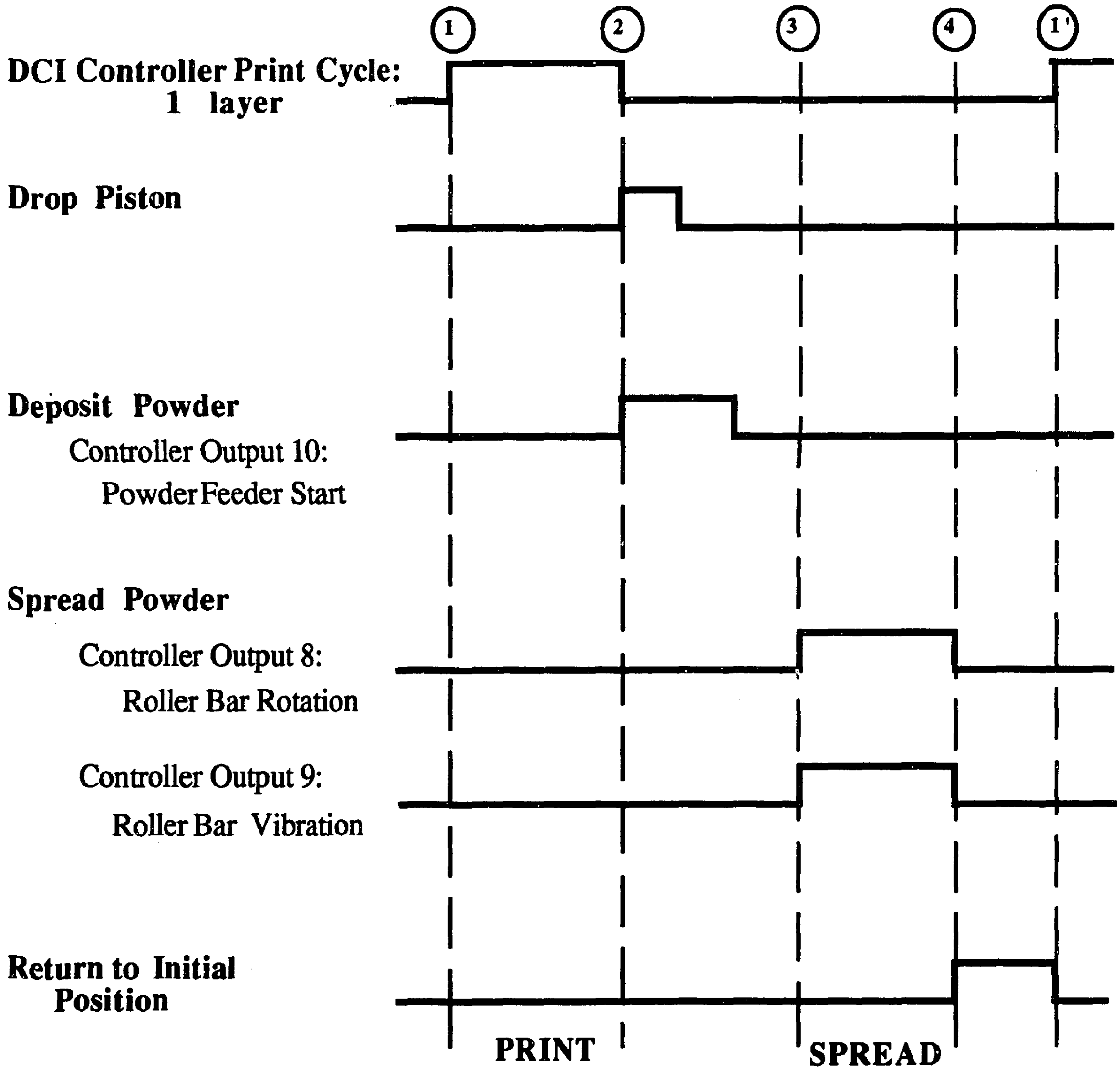
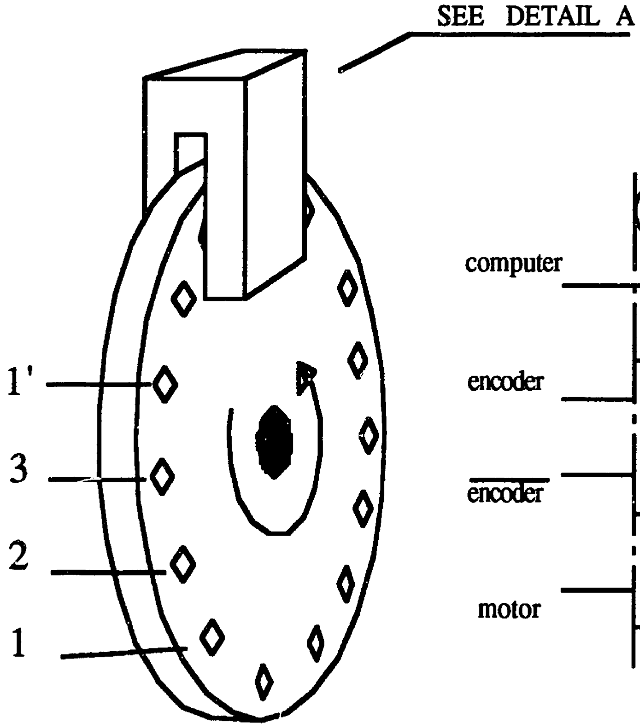
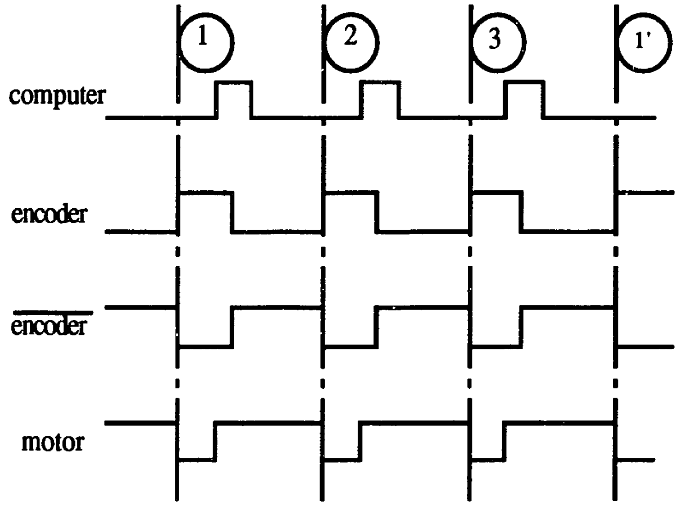


Figure 4. Timing Diagram for One Print Cycle

To insure that a precise volume of powder is deposited by the hopper in each cycle, a rotary-position encoder is mounted on the paddle wheel. The encoder wheel has holes which match up with the paddles, an optical sensor provides a signal to indicate the position of the encoder wheel. Typically, four pockets of powder is the volume required for one layer. For this situation the encoded holes are placed at every fourth paddle. A short computer pulse starts the rotation of the paddle wheel and a signal generated by an optical switch stops the rotation. The powder feeder control logic is depicted in Figure 5 and Figure 6.

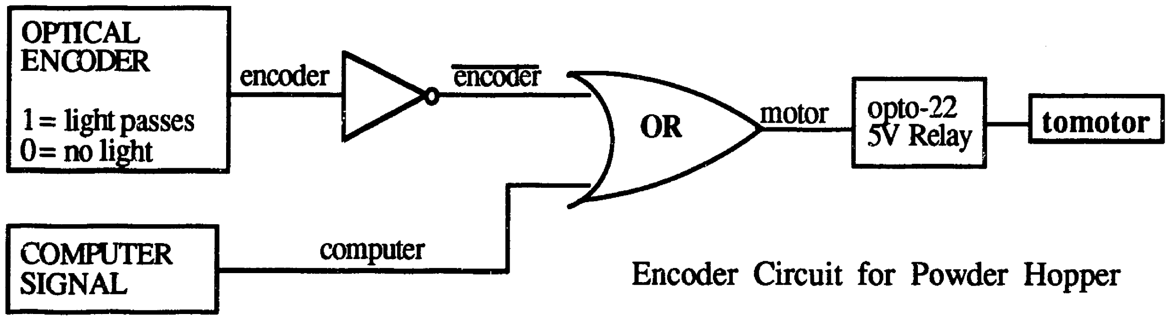




Powder Deposition Logic:

motor = computer + $\overline{\text{encoder}}$

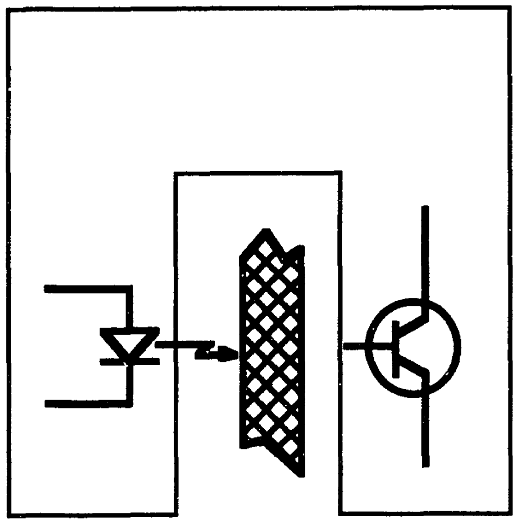
	computer	encoder	$\overline{\text{encoder}}$	motor
lightpassesencoder hole	1	1	0	1
nolightpasses	1	0	1	1
light passes encoder hole	0	1	0	0
no light passes	0	0	1	1



Encoder Circuit for Powder Hopper

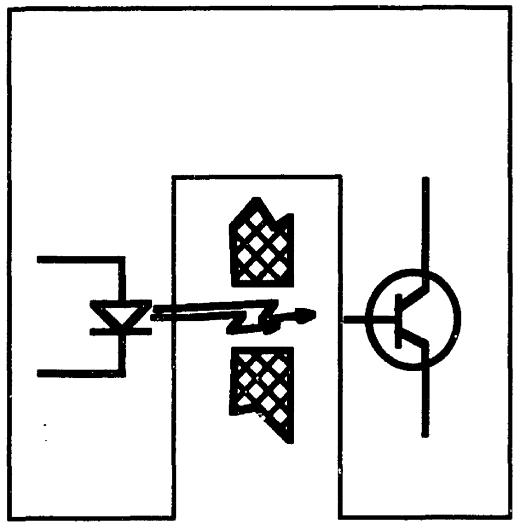
Figure 5. Powder Feeder Control Logic

encoder
low



Encoder signal is low when passage of light
is blocked by wheel

encoder
high



Encoder signal is high when light passes
through encoder holes in wheel

Detail A: Opto Switch

Figure 6: Detail of Optical Switch Operation

3.3 Roller Bar and Vibration

With the addition of cantilevered platforms to allow multiple fixturing to the slow-axis, the counter-rotating rod was mounted at a fixed height slightly above and square to the piston walls. An electromagnetic rod-vibration system was mounted in line and implemented as well. Previous research indicated that vibration of the counter-rotating rod achieved a denser packing of the powder layers than the counter-rotating rod alone. Denser powder packing allows denser parts and greater part strength. Density control could possibly be achieved using controlled vibration, varied volumes of deposited powder, or variable rod rotation and traverse speeds. Density control, as well as binder per unit volume, controlled through binder flow rate, would allow custom tailoring of shells and cores to particular casting and leeching processes.

The 1/4 inch stainless steel rod is mounted in bearings set in leaf spring supports. The rotation is driven by a 24V DC motor through a flexible coupling. The rod and motor are vibrated by a horizontal vibration forcer by Ling Dynamic Systems. Both the motor and the rod are mounted on leaf-springs to allow transverse vibration of the system along the axis of the rod. The mechanism is vibrated by a dynamic solenoid at a frequency set from a frequency generator.

3.4 Powder Feeder

The powder feeder consists of a paddlewheel agitator in a tapered hopper as shown in Figure 7. The paddle wheel is driven by a 24V DC motor through a small belt drive system. The paddle wheel shaft is aluminum and the paddles are teflon, teflon was chosen for its compliance and resistance to corrosion and contamination. The construction of the paddlewheel is shown in Appendix A. The teflon paddles are secured in place by deforming the metal along the grooves with a center-punch. The volume of the hopper is on the scale of that of piston; it holds about 38 cubic inches, about one and half times the volume of the piston.

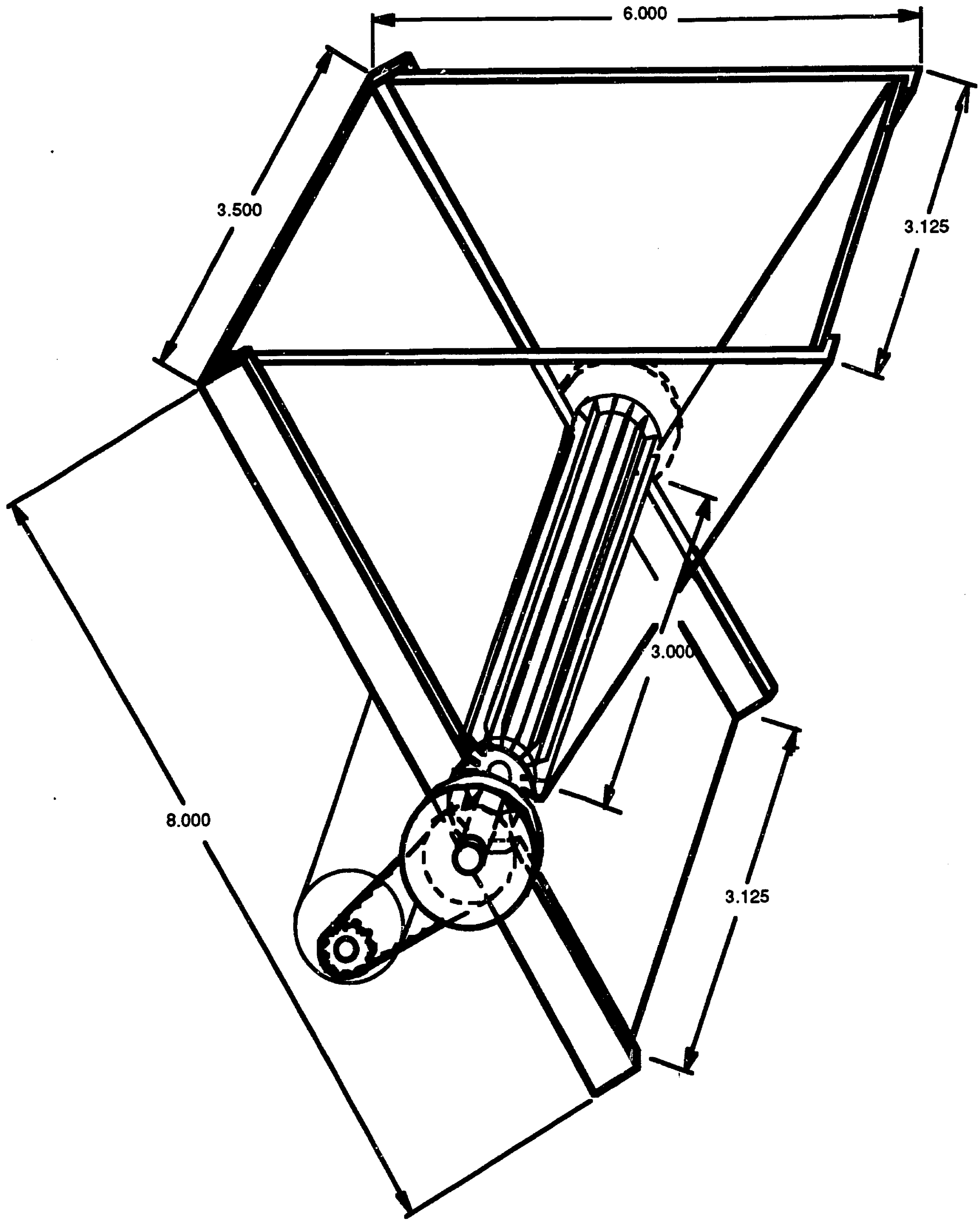


Figure 7. Powder Hopper

The hopper is constructed from aluminum plate, the back plate and trough is a continuous trough milled 3.5 inches wide and 3/8 inch deep. A thin strip of rubber is stretched taut and fixed in the groove. The compliant teflon flaps of the paddle wheel scrape on the rubber strip as the wheel turns. At least two paddles are always in contact with the rubber strip thus preventing the escape of powder. The triangular side walls are fixed to the back plate to create a tapered hopper. A one inch diameter paddle wheel the width of the hopper is mounted in the tapered bottom of hopper; the paddle scrapes a groove, of 1/8 inch depth and radius one inch, milled in the back plate of the hopper. A rubber flap fixed to bottom of the angled front wall prevents the escape of powder as it contacts the paddles. As the wheel turns, a pocket of powder is captured between two paddles and emptied into the trough. Powder is dropped in discrete volume increments or pockets, accurate continuous feed is not possible with the paddle wheel. A 3 inch x 3 inch layer .007" thick is the volume of approximately four pockets of powder.

4. Conclusions

The powder deposition system developed works well for the current Three Dimensional Printing Machine. The powder deposition system is versatile to allow variation of the spreading process parameters and experimentation with powders of varied characteristics. Almost any powder and particle size may be dispensed by the hopper. Spreading parameters such as roller rotation and traverse speeds as well as the vibration magnitude, frequency and direction may also be varied. For a given set of parameters, the resolution of the powder volumes dispensed and repeatability of the powder layers is very good. As such, the powder deposition system meets the wide range of experimental needs of the project. Future versions of the machine may require more precise powder deposition limited to a specific powder or set of powders. In particular, of the available dispensing methods presented, vibrational feeding is excellent for a given set of powder characteristics.

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Osborne, J.M., McGraw, H.R., and Draut, C.F., "Automated Device for Dispensing Precise Amounts of Powder," ASME paper 72-MH-18, 1972, pp. 1-8.

Solids Flow Control, Mass Flow Feeding and Control Specialists, Charlotte, NC. Company literature on Siletta live-base feeders.

Appendix A. Powder Feeder Paddle Wheel Assembly

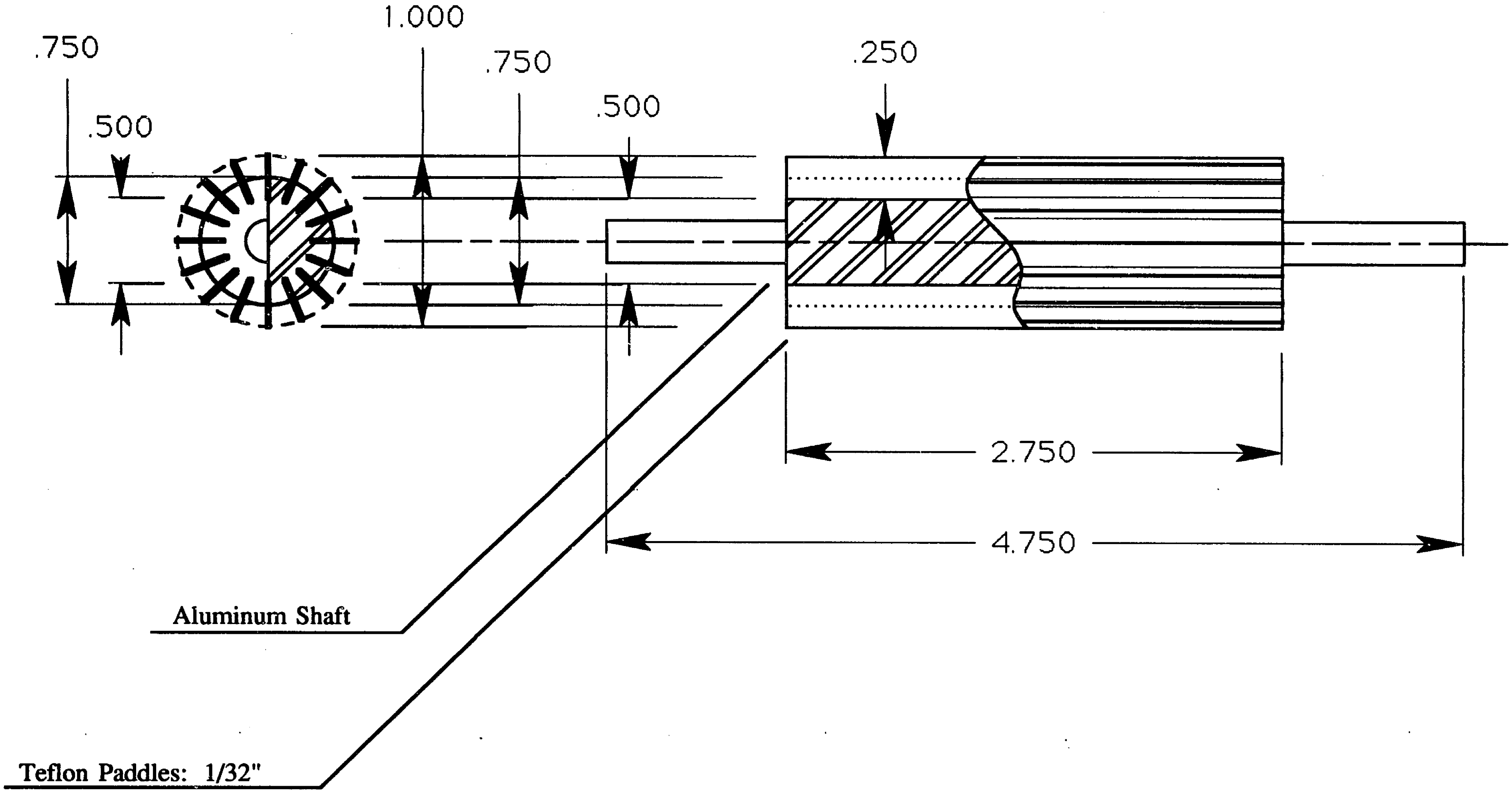

Figure 8. Powder Feeder Paddle Wheel Construction

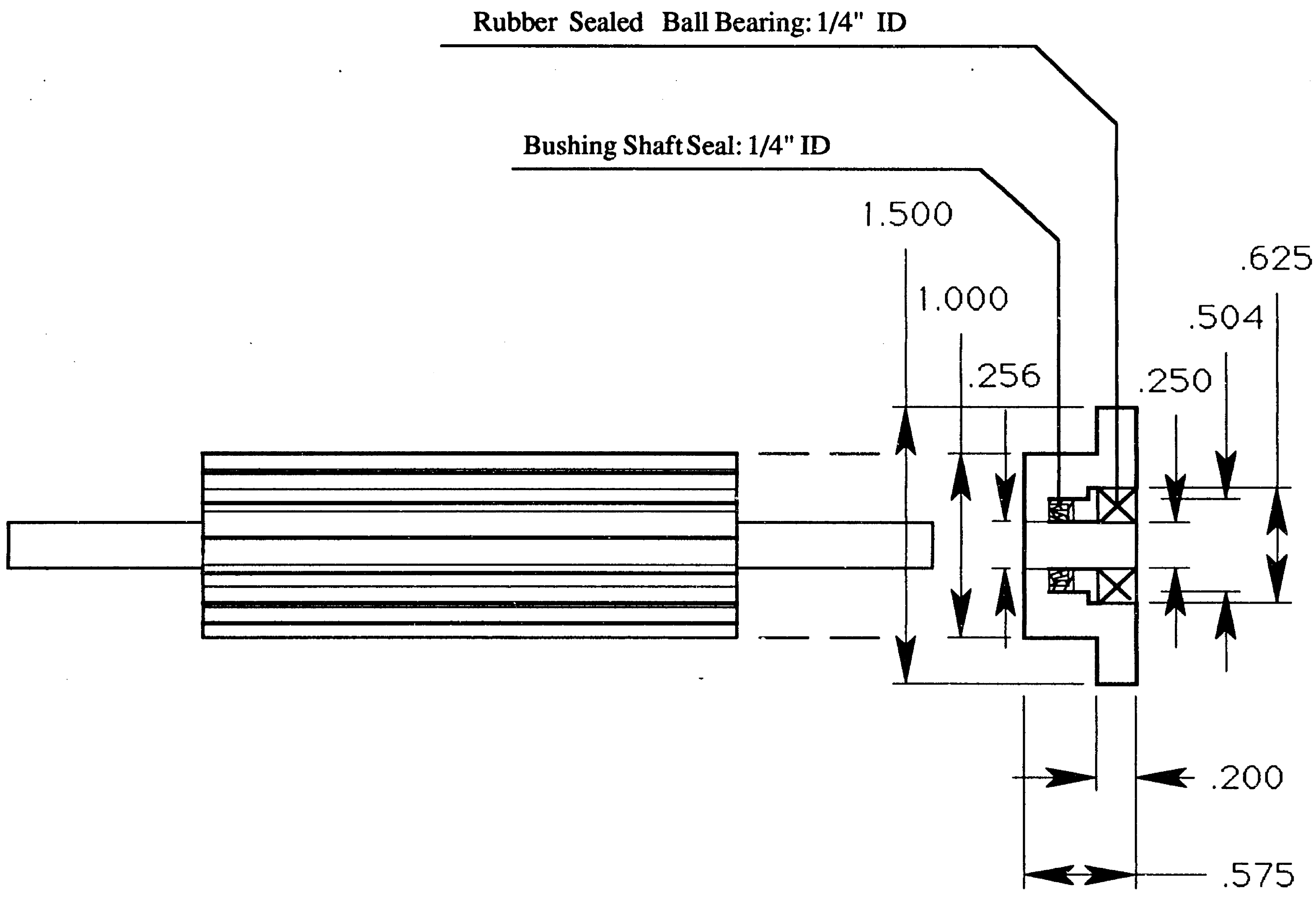

Figure 9. Powder Feeder Paddle Wheel and Bearing

Appendix B. Powder Hopper Parts Drawings

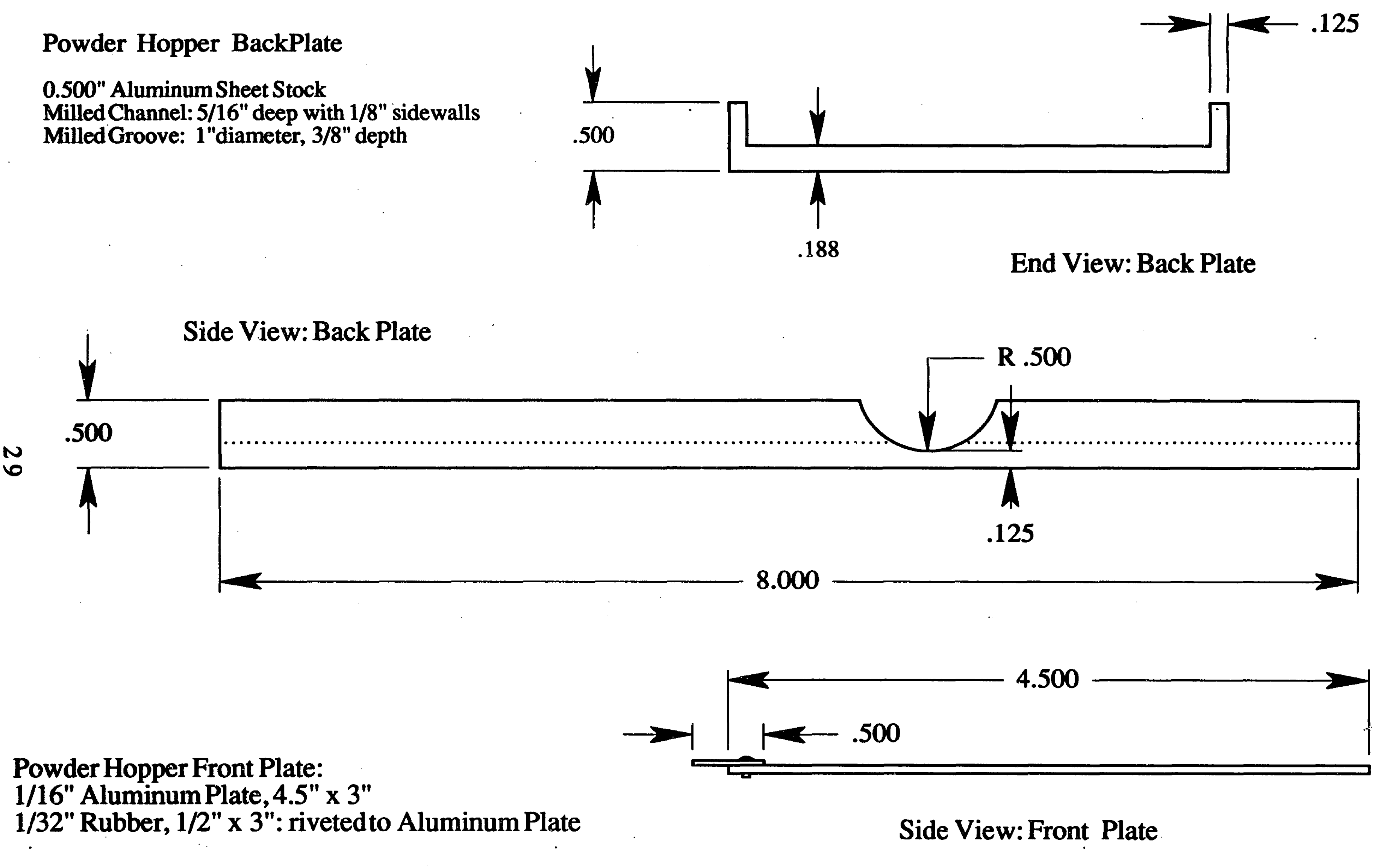

Figure 10. Powder Hopper Parts Drawings: Back and Front Plates

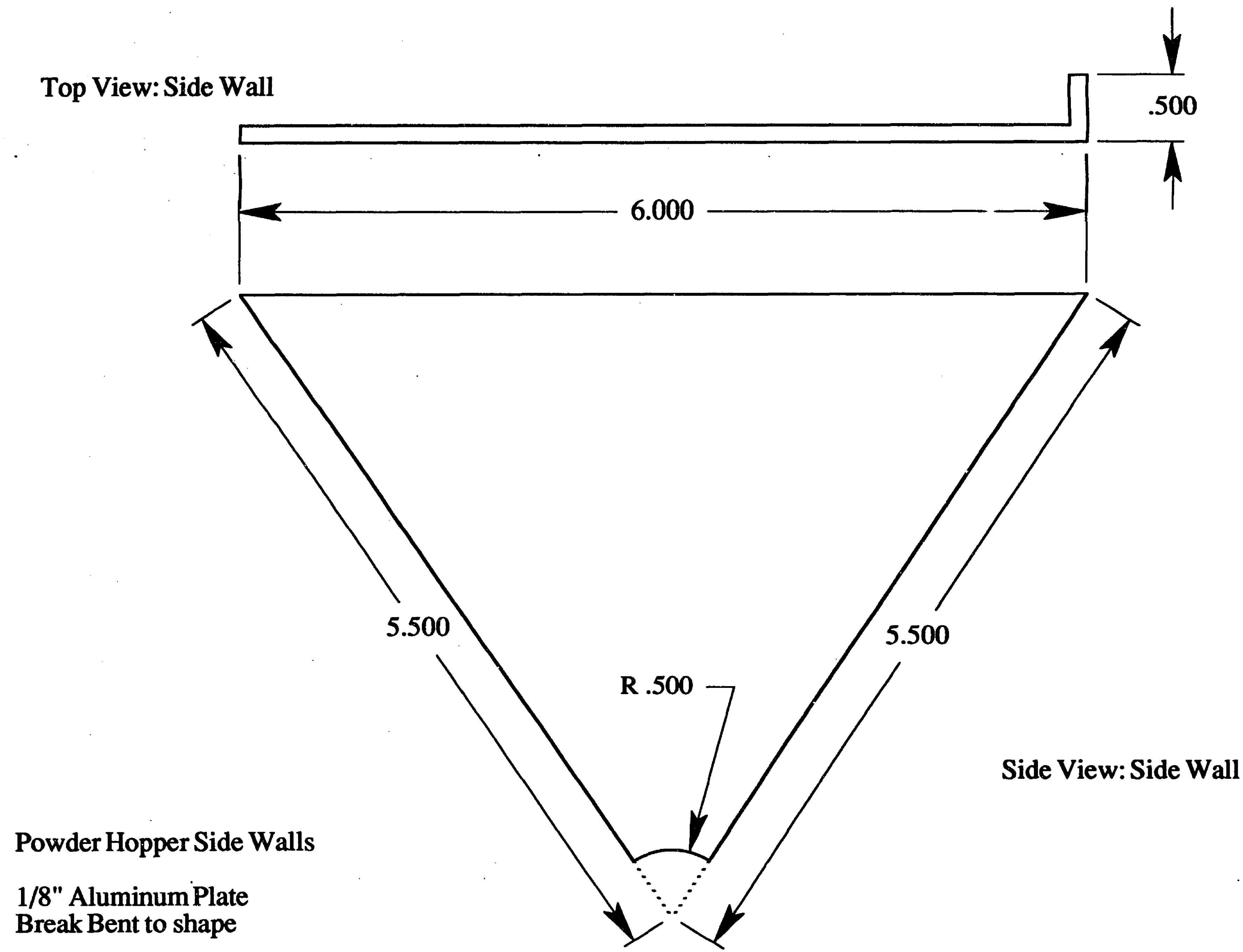

Figure 11. Powder Hopper Parts Drawings: Side Walls

Appendix C. Powder Deposition Circuit Diagram

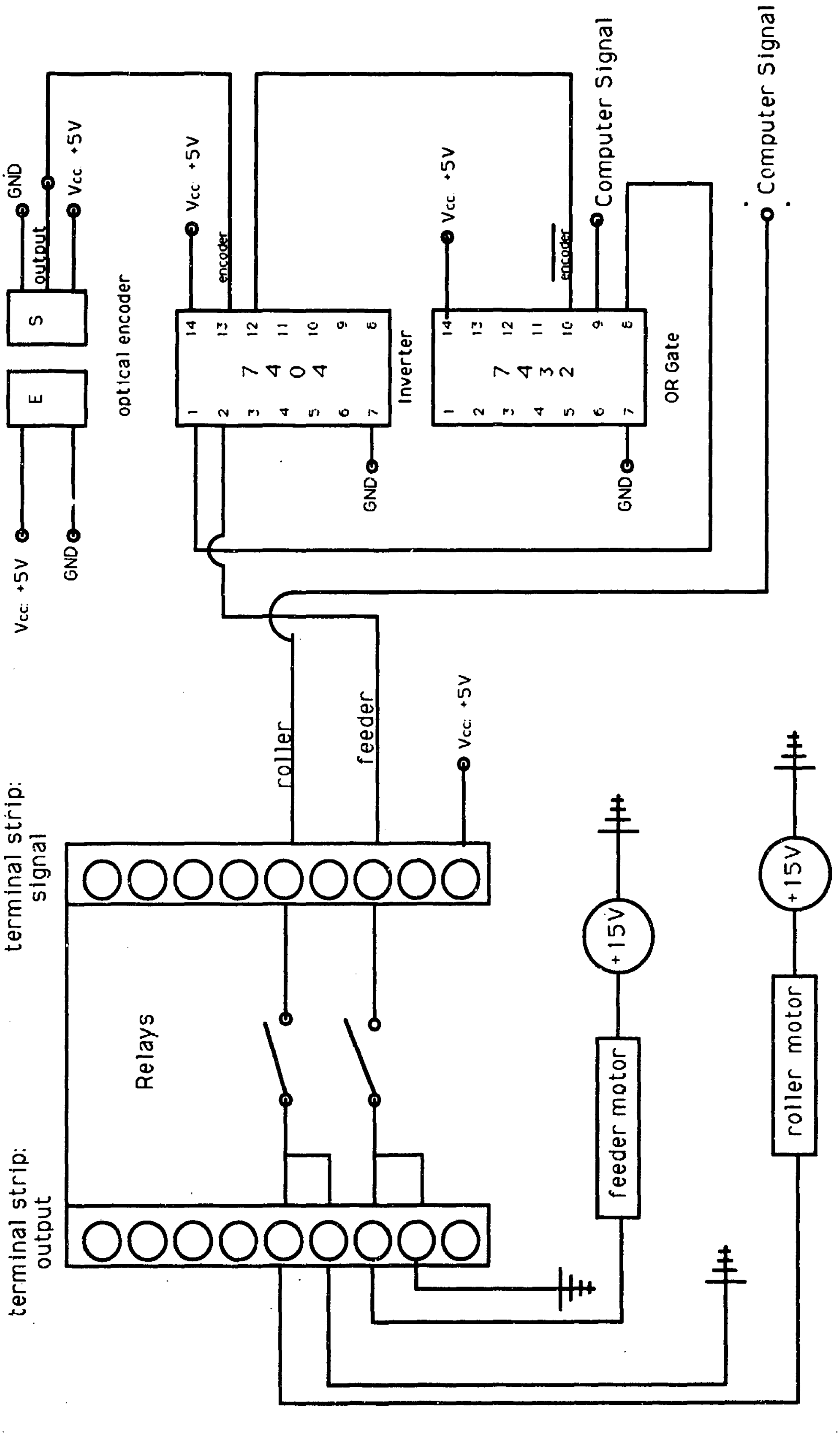

Figure 12: Circuit diagram of Powder Deposition System

Appendix D. Photographs of the Powder Deposition System

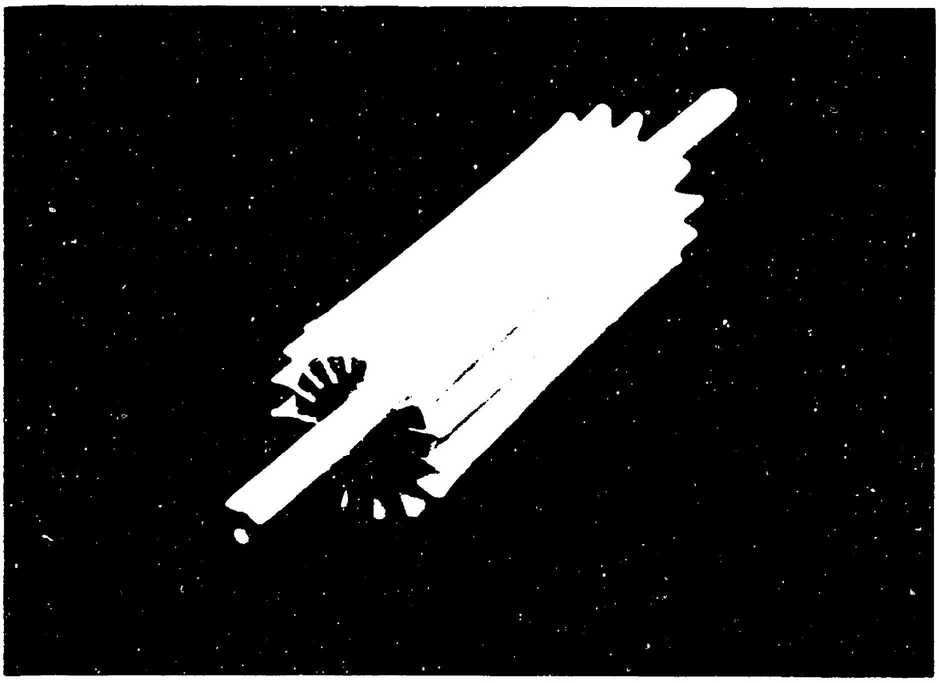

Figure 13. Powder Feeder Paddle Wheel

Figure 14. Powder Deposition System

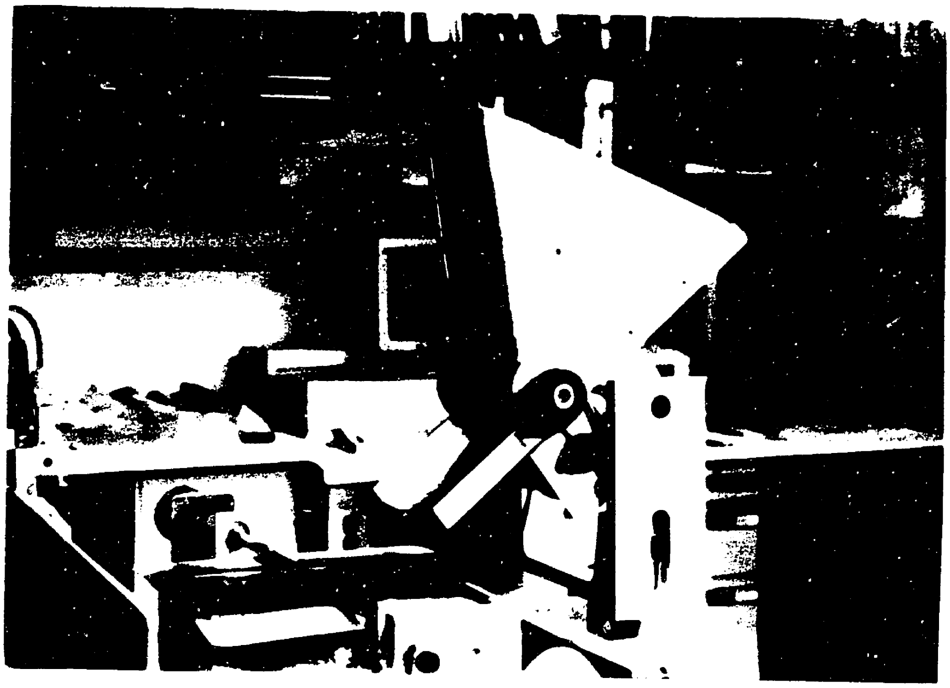

Figure 15. Powder Deposition System: Side View