THE SAND-PAINTER: Two-dimensional powder deposition

Joseph Pegna
Stéphane Pattofatto, Raphael Bergé,
Carol Bangalan, Henry Herring,
Mathias LeSaux, Jason Engler

Department of Mechanical Engineering, Concordia University
Montréal, Québec H3G1M8, Canada
Tel: (514) 848-4193 – Fax: (514) 848-3175
email: pegnaj@alcor.concordia.ca

Abstract: *The Sand-Painter project addresses the problem of pointwise deposition of multi-material powders in layered manufacturing. This approach is key to the development of selective aggregation processes capable of producing functional prototypes with internal sub-structures not achievable by any of the extant layered manufacturing processes. The solution adopted for this project is an automated version of the ancient Native American art of sand painting. Preliminary results pertaining to powder flow and deposition characterization are presented. A proof of concept multi-material deposition process was demonstrated.*

Keywords: *Sand painting, layered manufacturing, SLS, 3D-Printing, selective aggregation, multi-material, multi-modal structures, functionally graded materials., mechatronics.*

1 PRE-HISTORY OF THE SAND-PAINTER PROJECT

The Sand-Painter Project is the extension of a long-term, low-budget undergraduate research supervised by the lead author between 1993 and 1997 [Pegna, 1995a],[Pegna, 1995b],[Pegna, 1997]. The main objective of this project was a low-cost investigation and evaluation of the avenues left unexplored in the Solid Freeform Fabrication community, especially as they pertain to the fabrication of large, multi-material, functional prototypes from bulk material.

For more details on the rationale and methodology of the preliminary research, the reader is referred to the 1995 Solid Freeform Fabrication Proceedings [Pegna, 1995a]. The main outcome of this and other [Rock and Gilman, 1995] works was a proof of concept that patterned deposition of powder layers can be used as the basis for free-form fabrication. Two other important predictions came out of [Pegna, 1995a]. First it showed that the proposed approach lends itself to the fabrication of multi-material structures by either processing multiple powders in a single layer, or by inclusion of prefabricated sub-structures. Second, the volumetric flowrates experimentally feasible were compatible with the fabrication of large functional structures, and made the technology a viable alternative for construction automation.

An incidental result came from the low-cost constraint which led to the choice of cement and sand as the building materials. The processing of each patterned layer with water vapor resulted in a concrete with unusual and anisotropic material properties [Pegna, 1997]. Though these results would need to be confirmed by repeating the experiment, they illustrate the potential of multi-powder processes in the creation of hitherto undiscovered material properties.

Regardless of researcher and project however, one main obstacle remained after 1997. Powder deposition had been primarily effected by ad-hoc combination of masks, manual hoppers, or both. A pointwise, low-volumetric flow powder deposition system was still needed to automate the proposed free-form fabrication process. This has now become the primary objective of the Sand-Painter Project.

The Sand-Painter Project is therefore geared toward the investigation of powder handling, flow, and deposition characterization. The main challenge of this project lies in the geometric characteristics and flow ranges needed for free-form fabrication, which are outside the commonly studied types of particulate flows. The benefits of this research however go well beyond the proposed free-form fabrication processes of [Pegna, 1995a], and [Rock and Gilman, 1995]. Indeed, all current powder-based free-form fabrication processes rely on a powder blanket deposition. The availability of multi-powder patterned deposition is a generic increment to existing powder-based layered manufacturing technologies.

Organization of the manuscript: The main objective of this paper is to report on the experimental design of a two-dimensional powder deposition apparatus. Whenever existing results support it, a characterization of the flow and deposition will be presented. To this end this paper is organized in four main parts. Section 2 will review the prior art in powder deposition, and in powder flow control. Section 3 introduces the vibratory L-Valve concept, which is the keystone of the proposed process. Section 4 focuses on experimental characterization of the powder flow. Section 5 presents preliminary results in characterization of the deposit geometry, as well as a proof of concept of multi-material deposition.

2 Prior Art

2.1 Powder Deposition.

Seldom has the expression "prior art" taken as literal a meaning as it will in this section. A review of prior powder deposition techniques to form prescribed 2-dimensional patterns turned almost exclusively to the graphic arts. Of all these the only bone fide automated technique for 2D pattern deposition is the well-known and well documented electrostatic drum used in laser printers. All other approaches to depositing patterns consisting of different powders turn out to be ancient art forms. The first and most common form is enamel work, originating it seems with the Mycenaean (Cyprus) between the 13th and 11th century BC. A similar art form consisting of depositing lose powder patterns has been practiced as part of religious rituals by Navajo Indians and Tibetan monks for at least 1000 years. Among the Navajo Indians, it is known as "Sand-Painting", while the Tibetan word for it is "Mandala". While none of the above graphic art forms would qualify as modern manufacturing technique, they are definitely part of our world heritage of manufacturing science. As such, they are worth investigating in the context of freeform fabrication and we shall now review them in details.

Electrostatic drum: The electrostatic drum used in laser printers allows for accurate (about a 1/1000th inch or 25μm at best) location of a small quantity of non-conductive powders (spot diameter 25-100μm x by up to 10μm high). However, given the material restrictions, low volumetric build rate, and cost, this approach to powder deposition was not pursued further.

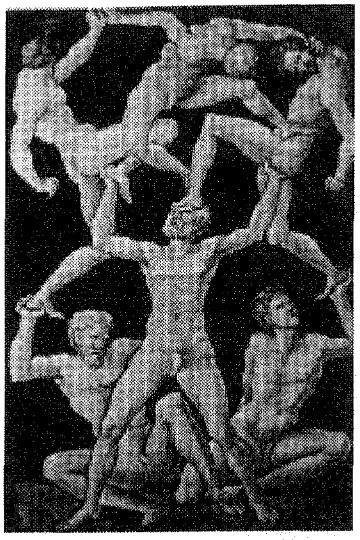


FIGURE 1. Details of "Les Acrobats;" Enamel work in Grisaille from Limoges, France c. 1550 (Walters Art Gallery, Baltimore, 43.5cm x 30.5cm)

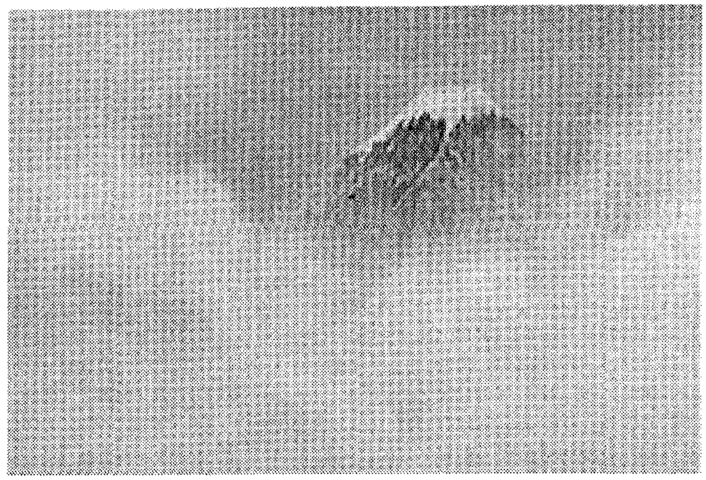


FIGURE 2. Details "Mount Fuji seen through clouds." Lineless cloisonné by Namakawa Sosuke, 1893. Tokyo National Museum (63cmx113.6cm).

Enamel work: Enamel work is a graphic art form whereby colored glass powders are deposited into patterns drawn on a metal plate. The deposit is subsequently fired to fuse the glass; thus preserving the design upon cooling and solidification. This art form appears to have been initiated by the Mycenaean between the 13th and 11th century BC, perfected by the Celts between the 3rd and 2nd century BC, and reached its pinnacle during the European Renaissance, even rivaling oil paint in details. A sample of European art is shown in Figure 1. Enamel work appears to have migrated out of Europe and into East Asia, where it also evolved into an elaborate art form illustrated by Figure 2

FIGURE 3. Anglo-Saxon champlevé enamel circa 650. British Museum 6cm.

For the most part, the patterning of powder deposits is done by blanket deposition over areas delimited by masks, retaining walls or groves. The *"cloisonné"* process uses thin metal strips that are bent to form the outline for the decorative pattern, and then attached to the base metal plate where they form miniatures cofferdam-like cells. Each cell is then filled with powders. The *"champlevé"* process is the opposite. Instead of walls being added, groves are gauged into the metal base, and then filled with colored glass powders. The cloisonné and champlevé processes allow multiple powders to be deposited in adjacent cells, but without mixing. Hence only discontinuous coloring is obtained as illustrated in Figure 3.

A few alternative processes allow gradation of color —i.e. of powders— and are used either alone or in addition to cloisonné or champlevé; most notably, the *"Painted Enamel"* and *"Grisaille Enamel"*. In the painted enamel process the various color enamels are applied in wet powdered state by masking or brushing without metal strip or ridges separating them. Each layer is allowed to dry before the next is applied to avoid blurring of the boundary. Grisaille enamel provides a wide range of contrast by depositing white enamel over colored enamel, which is then selectively removed or hashed before firing. In that respect, Grisaille enamel does not affect the resulting color by changing materials, but rather by varying the mixing ratio of two colors.

For the most part, powder deposition in enamel work is effected though blanket deposition into 2-D molds, be they masks, ridges or groves and do not differ fundamentally from the work intensive method used by [Pegna, 1995a].

Sand Painting: Another form of ancient graphic art offers insights into powder deposition. Although the history of sand-painting is far less well documented than that of enamel works, it appears to have developed independently in different parts of the world for a at least a thousand years. The approach taken for this alternative art form is to deposit dry powders pointwise by using hoppers, sometimes rearranging it with small brushes. Curiously similar in their techniques and religious natures, sand paintings by Navajo Native Americans of New Mexico, and Mandalas done by Tibetan monks are left as lose powders for the elements to partake.. With the advent of tourism, Navajo sand-painting can now be found in a more resilient version, with glue sprayed over it to preserve the design. Figure 4 illustrates the level of detail and complexity achieved with Navajo sand-painting.

The size and complexity exhibited by Tibetan Mandalas clearly illustrates the potential of pointwise powder deposition in creating two dimensional patterns. Figure 5 shows the result of three Seraje monks work over four weeks in creating a Mandala. The automation and mechanization of this art form is in essence our project goal.

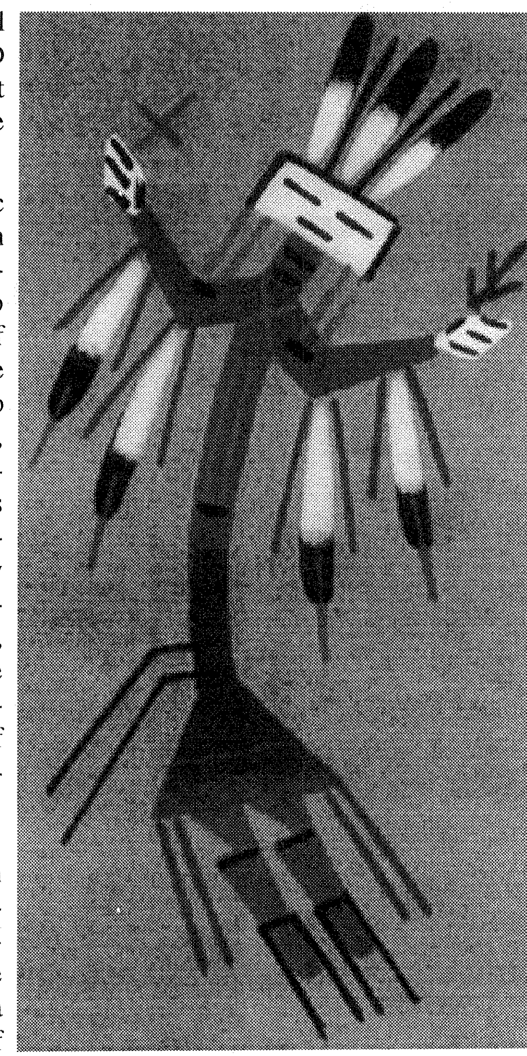
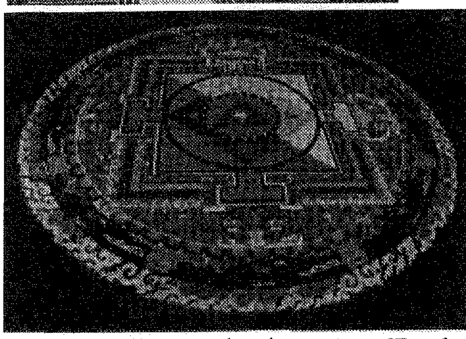


FIGURE 4. Sample Navajo sand painting (From the author's collection).

2.2 Powder transport and flow control

In pursuit of our goal of automated Sand-Painting, one of the critical issues to be addressed is that of bulk material transport to its eventual destination in the deposit. This is a new problem in the freeform fabrication arena, which has only seen blanket deposition and compaction by counter-



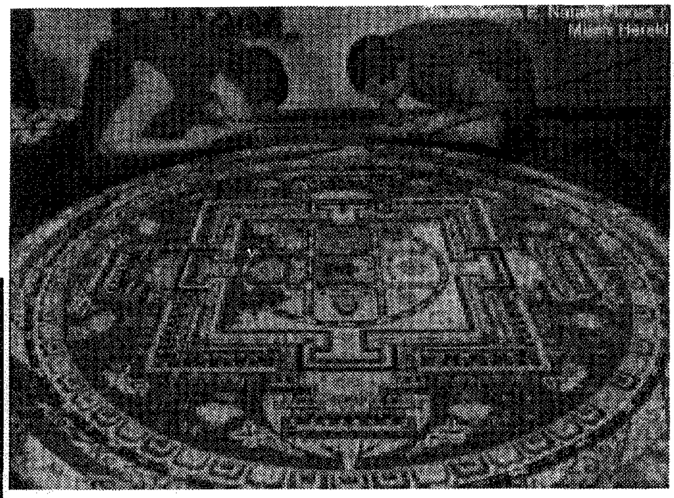
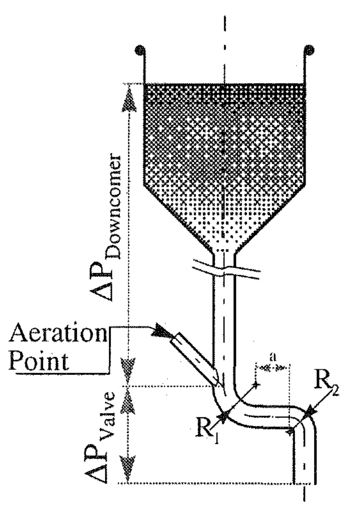


FIGURE 5. Sample Mandala decorative pattern illustrating size and complexity of feasible designs (Source: Miami Herald).

rotating roller mechanisms (see [Deckard and Beaman, 1987], or [Sachs et al., 1990] for example.) The state of the art in granular material flow can contribute to our research both from the point of view of understanding the flow mechanisms, and from the point of view of flow control, or valving. The former really belongs to a branch of mechanics which is best addressed by a specialized reference such as [Brown and Richards, 1982], [Mason and Woodcock, 1987], or [Hans, 1990]. The latter question of valving and flow control is of more immediate concern and will be addressed now.

Valving of granular material flow: The deposition mechanism sought for our free-form deposition process is well outside of the mainstream applications in bulk material transports. While the electrostatic drum provides a resolutions that equals or surpass freeform fabrication processes, the build rate (about 10μm per pass) is so minute is so minute that the process may only apply to micrometric devices. Alternate flow control processes that can support on/off or flow modulation are intended for large flowrates (0.1 to 10^3 liter/s) or fluidized powder flows in which the particulates represent only a small fraction (usually <10%) of the volume. A particularly interesting alternative for our purpose is the L-Valve shown in Figure 6.



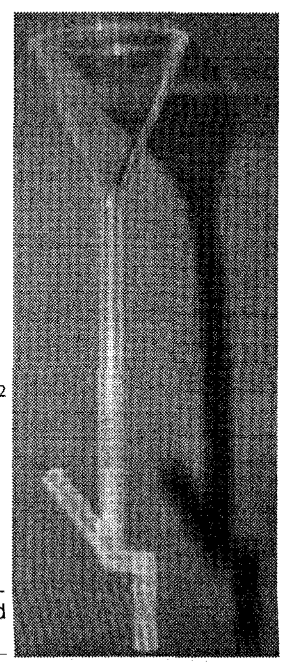


FIGURE 6. Pneumatic L-Valve: Basic concept and implementation.

A typical L-Valve consists of a downcomer section and a characteristic elbow giving the valve its name. At the junction of the downcomer and elbow is inserted an aeration point through which a jet of pressurized fluid can be injected. This injection fluidizes the powder bed, allowing it to flow down the L-Valve. When the fluid injection stops, the powders re-compact and the flow stops. This type of valve allows on/off as well as modulated flow control over a wide range of flowrates and materials. Yet the typical use for L-Valves involves flowrates at least one order of magnitude larger than that of concern to our design.

Experimentations were conducted with vented glass L-valves with diameters 1, 2, and 3 mm downcomers such as illustrated in Figure 6. The powders used were 33μm and 200μm spherical glass beads, uncalibrated silicon carbide, cement and sand powders. The source of pressurized air was a fish tank air pump with an adjustable restriction for pressure regulation. The results however were far from satisfactory. While on/off control was somewhat achievable. Even at pressures a low as 1cm H_2O above ambient, the fluid flow was dominant. Both flow and deposition of the powders was highly irregular and of no practical use for the range of flowrates.

The main conclusion from this section is that none of the existing powder flow control technologies could address our required volumetric flowrates and deposition requirements. Our main challenge therefore would be the invention of flow control and deposition processes that can serve our fabrication requirements.

3 VIBRATORY L-VALVE

In search of a satisfactory design to achieve powder handling and deposition within ranges needed for free form layer deposition, no solution were found in extant technologies; be it from coal, mineral, mining, food, cosmetic, or pharmaceutical industry. Yet the most ancient arts of sand painting, mandala, and enamel achieve feats of feature definition in powder deposits that rival oil paint in color definition and geometric complexity. The flowrates involved in sand-painting range from the mm^3/s to tens of cm^3/s. Feature definition ranges from the mm^2 (Figure 4) to a few m^2 (Figure 5.) How can such a performance be achieved with mostly rudimentary hand-tools?

Besides brushes and needles —mostly used to rearrange the deposit— the main instrument used for powder deposition is a small hand held hopper. It would seem therefore that vibratory fluidization is the most time tested technique for transport and deposition of powdered solids. This remark, and the L-Valve design naturally leads to the concept of vibratory actuated L-Valve, which is developed below.

FIGURE 7. Sample experimental vibratory L-Valve designs.

3.1 Design

The L-Valve design was implemented in various experimental versions intended to characterize both flow and deposition. Figure 7 shows some sample glass designs. An experimental design methodology was followed in this

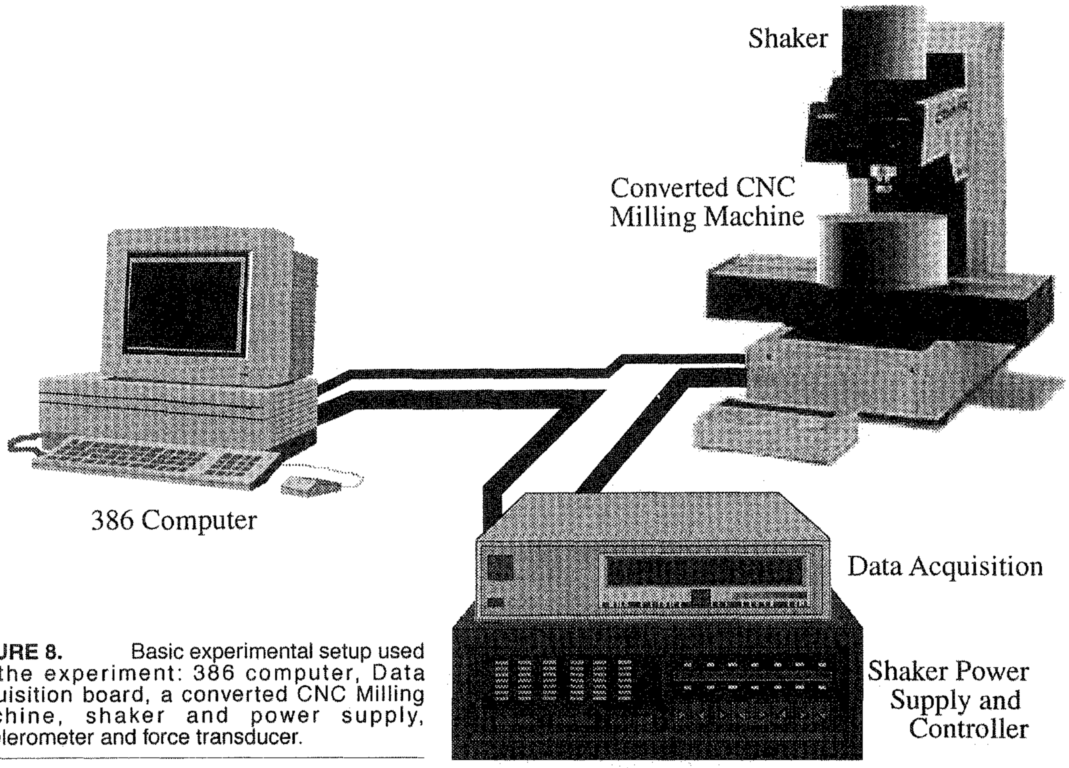


FIGURE 8. Basic experimental setup used for the experiment: 386 computer, Data acquisition board, a converted CNC Milling machine, shaker and power supply, accelerometer and force transducer.

study. Despite the use of a rational methodology, the number of data points needed is still such that we can only present preliminary results in this paper. Those results, as we shall see, are promising enough to warrant continuation of this study.

3.2 Experimental

The basic experimental set up is shown in Figure 8. The centerpiece is an old CNC CAMM3 milling machine in which the vertical spindle has been removed and replaced by a shaker. Control of the milling machine is effected by a 386 computer using G-Code. The computer also communicates with the shaker controller via an RS232 interface. In the initial implementation, real-time flow measurements were performed by means of a load cell accelerometer mounted in series with the hopper. The signal to noise ratio was such however that the only average results were of any use. A further verification of flow rate was done simply by timing the deposition of a known mass of powders. Powder flow visualization was done using a stroboscopic flash synchronized to the shaker; an example of which is shown in Figure 9.

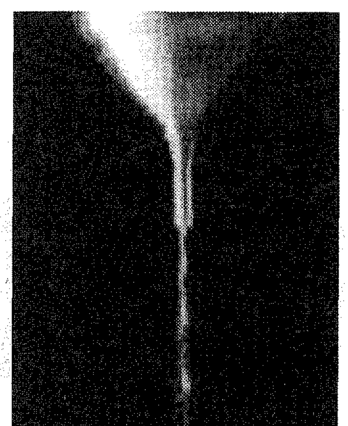


FIGURE 9. In-phase stroboscopic view of the powder flow through a straight downcomer.

Note that an indirect implication of this experimental setup is the possibility of using a regular CNC machine tool as the support for layered manufacturing. Indeed, the proposed approach offers the prospect of an inexpensive tool kit alternative to dedicated rapid prototyping machines, assuming of course that the shop is already equipped with an available CNC vertical milling machine or lathe.

4 Experimental Flow Characterization

When used in conjunction with powders, vibrations are mostly intended for compaction of a bed. In our instance, vibrations are called upon for fluidization. Preliminary experiments had shown that at certain combinations of powders and hopper mass, vibrations could be used as a mean of modulation or on/off control.

Table 1 below outlines the key parameters which determine the outcome of the powder flow through the downcomer, and which must be controlled.

TABLE 1. Process parameters affecting powder flow through the downcomer.

FLOW CONTROL PROCESS PARAMETERS			
POWDERS			
Size	Geometry	Material/Density	Hygrometry
HOPPER			
Mass	Downcomer Geometry	Dimensions.	
VIBRATIONS			
Amplitude	Frequency	Waveform	

We begin by conducting a series of experiments, designed to expose the relationship between the flow rate and the process parameters. This experimentation is necessary as little data exists in the literature which can be used to formulate a complete deposition model. In future developments, a theoretical study of powder flow must be carried out to compare with our experimental results. The ultimate goal, of course, is that the analytical model be simplified and perfected through this comparison, so that, wherever possible, real-time numerical prediction of process parameters can be achieved. However, as all imaginable design cases cannot be predicted analytically, it is not realistic to obtain a complete model solely from theory. In the short term however, our goal is to obtain a set of design rules (in tabular/look-up form) to allow rapid computer control of the process. We seek to employ empirical solutions where results cannot be obtained analyti-

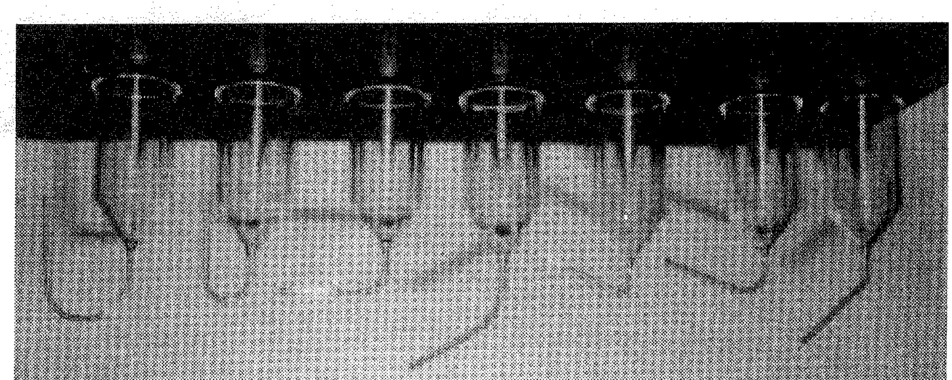


FIGURE 10. Sample hoppers developed for powder flow analysis.

cally. As dedicated sensing becomes available —e.g. real-time mass flow measurements— the model will be refined and adaptive control of the process can be investigated.

In order to perform a complete analysis of the powder flow however, a series of glass hoppers were fabricated with various 45° cone angle, various elbow radii and elbow angles, all using a ø1mm downcomer. A few sample hoppers are shown in Figure 10. The amount of data collection required for such experiments is so large however, that only straight downcomer results are presented here.

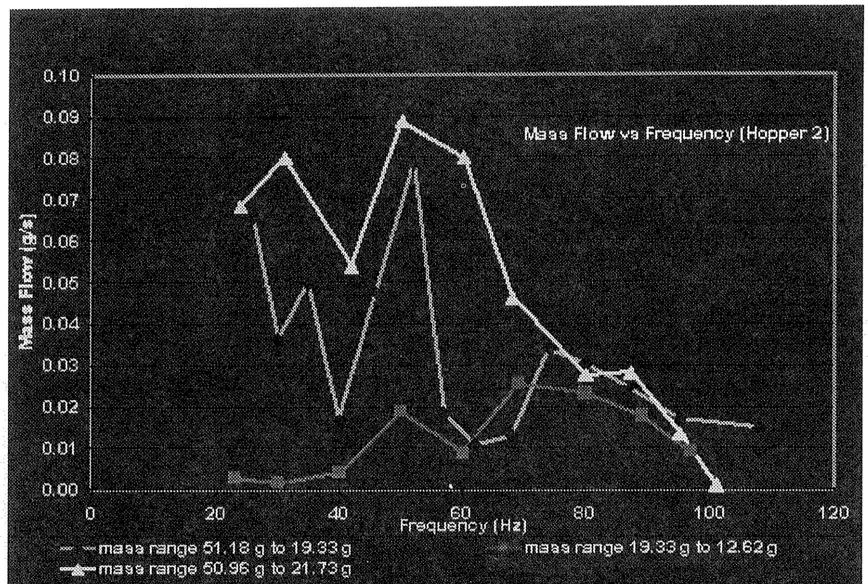


FIGURE 11. Sample mass flow rates vs. frequency plots for series of runs through variable hopper masses.

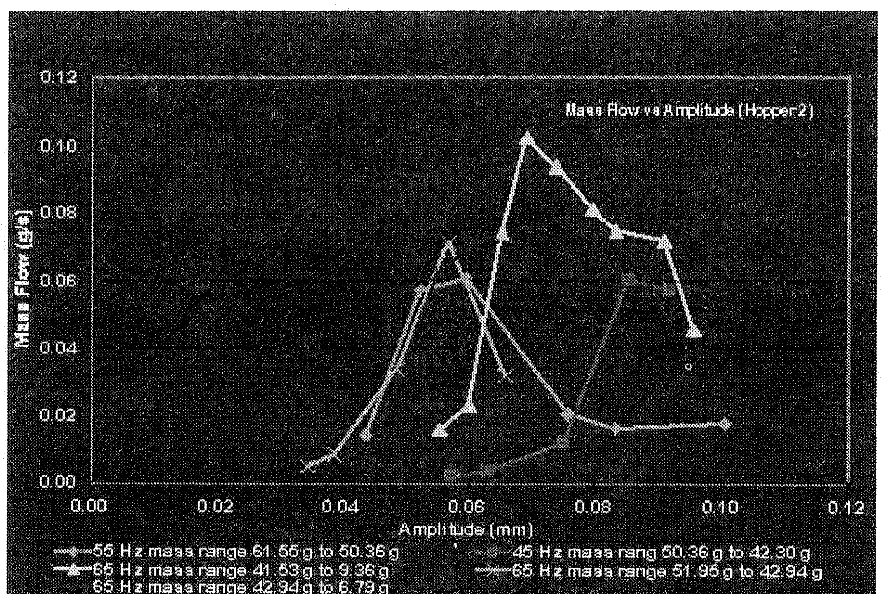


FIGURE 12. Sample mass flow rates vs. amplitude plots for series of runs through variable hopper masses.

Various types of powders were subjected to the experiment:

- ø22μm and ø250 μm spherical glass beads.
- Uncalibrated Silicon Carbide powders.
- Uncalibrated sand.
- Uncalibrated cement powder.

For the most part free gravity flow was observed with ø22μm spherical glass bead, as should be expected from the mechanics of granular material flow [Hans, 1990]. As the particle diameter increases to about one quarter of the diameter opening, the mechanics enters a domain outside classical powder flow analysis. Yet it is in this domain that the best flow control were observed, as shown by the diagrams in figures 11-15.

Hygrometry, while not measured, was critical to the flow of cement powder. Indeed, results with cement powders were best reproduced by first baking the powders.

One of the most challenging tasks in operating the experiment described herein is the real-time mass flowrate measurement. Typical mass flows are of the order of hundreds to tenth of gram per second while typical hopper masses vary from 50 to 150 grams.

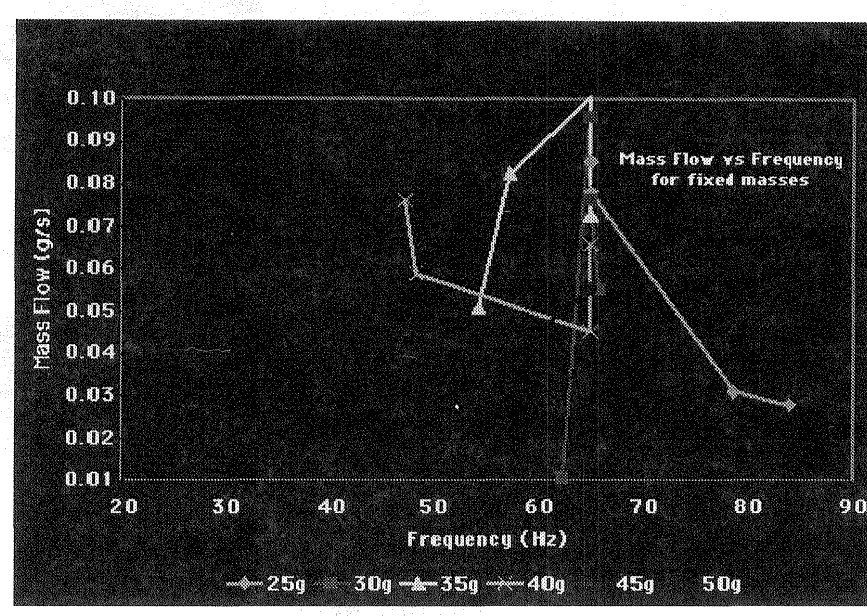


FIGURE 13. Mass flow vs. frequency characteristics interpolated for fixed hopper masses (but varying amplitudes).

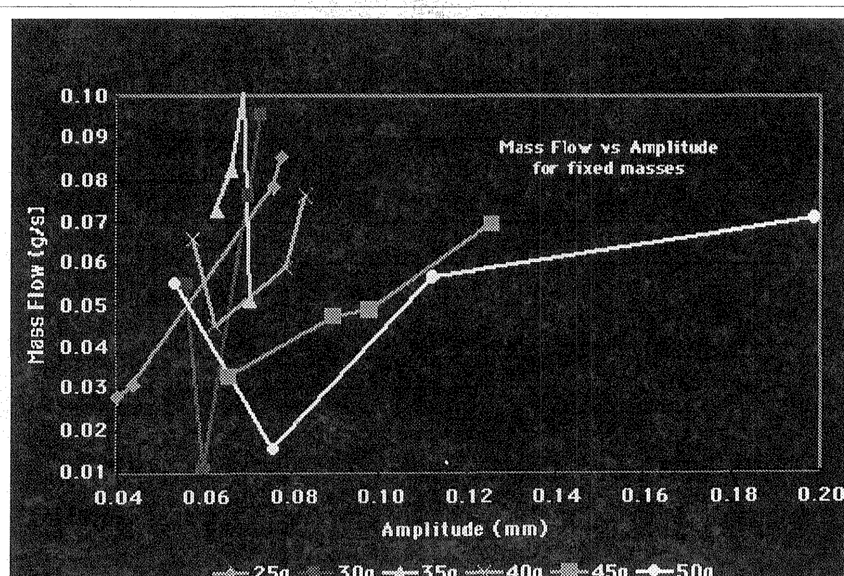


FIGURE 14. Mass flow vs. amplitude characteristics interpolated for fixed hopper masses (but varying frequency).

An accelerometer and force transducer mounted in series with the hopper offer only a tentative solution to this problem, as the significant fraction of the force transducer RMS signal is of the order of 10^{-7} to 10^{-6} for the typical flowrates, masses, frequencies, and amplitude state above. Hence measurements reported in this study are only limited to average measurements confirmed by timing the flow of a known amount of powder. This renders the characterization of powder flow through the downcomer particularly difficult since we cannot isolate instances of flowrates for a set hopper mass. The measurements exposed herein can only regarded as preliminary data, and further improvements to mass flow measurements will have to occur in order to pursue a rational experimental approach to the design.

Given the absence of a direct sampling method for flow rate measurement, exposing the relationship between powder flow and process parameters ends up being a laborious process illustrated by Figure 15. Each data point in figures 11 and 12 is obtained by timing a deposit and then weighing it. Since the flowrate is not known ahead of time and the hopper mass is varying, one can only measure flow rate at the expense of not knowing the mass precisely; an uncertainty principle of sort!

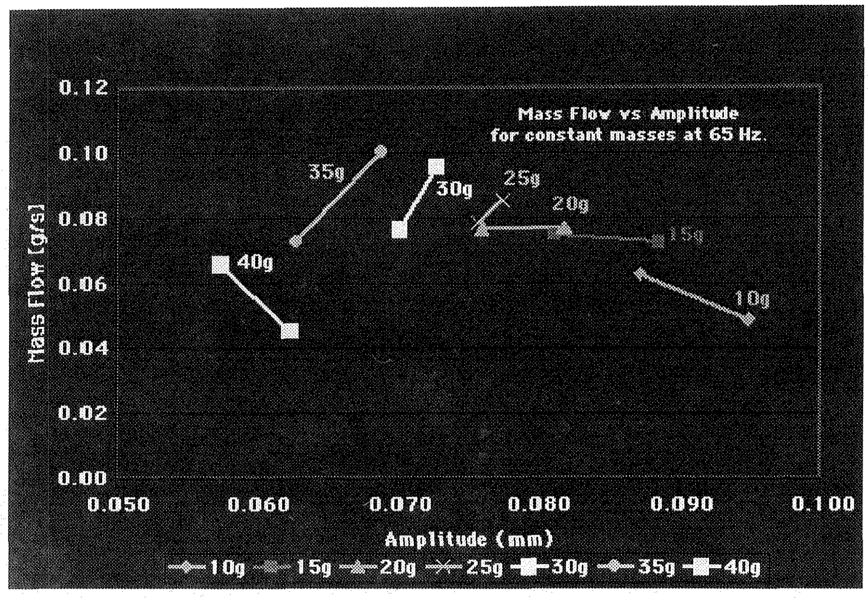


FIGURE 15. Composite of the mass flowrate vs. amplitude derived from Figures 11-14 for fixed hopper masses of 10, 15, 20, 25, 30, 35, and 40 grams, and fixed frequency of 65 Hertz.

On the basis of measurements in Figures 11 and 12, one can interpolate for fixed masses and plot flow rate vs. frequency in Figure 13, in which case the amplitude cannot be constant, or flow rate versus amplitude in Figure 14, in which the frequency cannot be constant. Only by interpolation of all the above data can we derive a crude 2 point measurement each for fixed mass at a set frequency. The summarized results are shown in Figure 15, which plots flowrate vs. amplitudes for set masses of 10 to 40 grams in 5 grams increments for a fixed frequency of 65 Hertz.

As limited as they may be, the results obtained to date demonstrate that the two main goals of our flow control are achievable:

- On/off control of the flow is achievable by either starting or stopping the vibrations, or by vibrating at a frequency or amplitude regime where no flow happens.
- Flow modulation can be achieved by either frequency or amplitude modulation.

Having determined that flowrate can be controlled, a truth that Navajo Natives and Tibetan monks discovered eons ago, we can now turn our attention to the object of this study: namely the deposit itself.

5 EXPERIMENTAL DEPOSITION CHARACTERIZATION

Before one even embarks on a characterization of the deposit, one must develop an understanding of the powder's transition from the downcomer to the substrate. Such an understanding also leads to a correct identification of relevant process parameters.

Experimental powder flow visualization is notoriously difficult. Given the periodic nature of the excitation though, it was legitimate to observe the flow and flight characteristics under a stroboscope. Such observation already provides a valuable insight into the deposition process. In Figure 9 for example, one can observe the flow through a straight downcomer using a stroboscope in phase with the vibrations of the hopper. The flow can be observed primarily as a series of "powder droplets" being stretched by gravity. While the flow is observed to disperse as it falls, it remains well focused and almost as narrow as the nozzle opening within a centimeter of the orifice.

FIGURE 16. In-phase stroboscopic view of the powder flow through a downcomer at 45°.

The flow from a downcomer at 45° illustrated on Figure 16 is representative of the types of hopper used by Navajo Native American and Tibetans for sand painting. This picture was taken using a stroboscope at twice the hopper frequency. It reveals that even though the flow has a horizontal velocity component, it exhibits a quasi-periodic nature. In particular the width of the flow is not uniform and reaches its minima at the nodes.Mark that the first node is indeed well focused and exhibits a diameter close to that of the orifice. This observation may help explain the level of fine details achieved by manual hopper deposition in sand-painting.

In order to study the geometric characteristics of the deposit, various automated scanning pattern depositions were used, as illustrated in Figures 17 and 18. Such patterns —rectilinear or circular— allowed direct measurement of the deposit width.

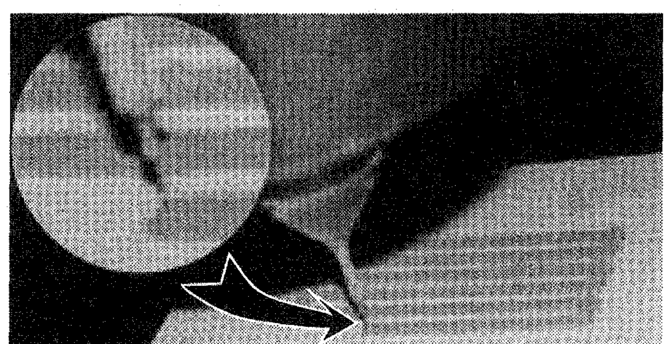
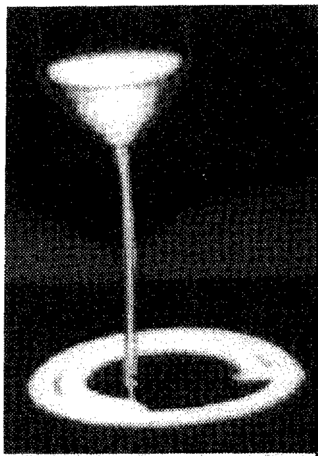


FIGURE 17. Sample scanning pattern used to measure deposit width (Type I Portland Cement on paper). The strobe flash was synchronized with the up swing of the hopper. The enlargement on the left shows a distinctive "droplet" pattern.

Beside downcomer diameter, slope and height, another factor involved in the shape of the deposit is the roughness of the substrate. To simulate a substrate roughness and establish this relationship, a variety of calibrated grit sandpaper were used as deposition substrates. It is understood at this stage that a sandpaper substrate represents a worst case condition as compared to a lose powder bed with greater energy absorption capacity. For the purpose of this paper, the results presented in Figure 19 only relate to 120 grit sandpaper.



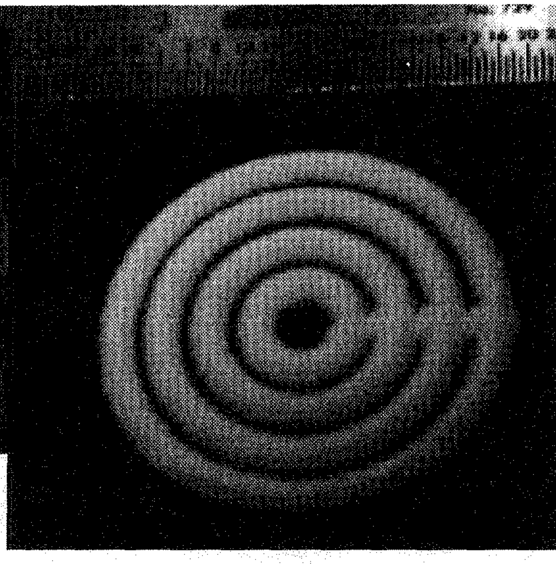


FIGURE 18. 220μm glass beads deposit on 400 grit SiC sand-paper.

Finally, one comes to what appears to be the most influential process parameters influencing the deposit geometry: Frequency and amplitude.

At first sight, it may appear reasonable to assume that a droplet of powder separates from the bulk during the downswing motion of the hopper, approximately synchronized with the reversal of acceleration. Hence the kinetic energy of the droplet would simply be proportional to its mass, the square of the amplitude, and the square of the frequency. This view is consistent with the results shown in Figure 19, parts A, C, and D. From the bottom up in part A, and top down in part C and D, the quality of the deposit at 52Hz (respectively 30Hz and 60Hz) decreases when the amplitude of the vibrations increases. Up to the point (respectively fourth, sixth, and eighth line from the top) where the area directly under the nozzle is devoid of any powder and the deposit is scattered around the line.

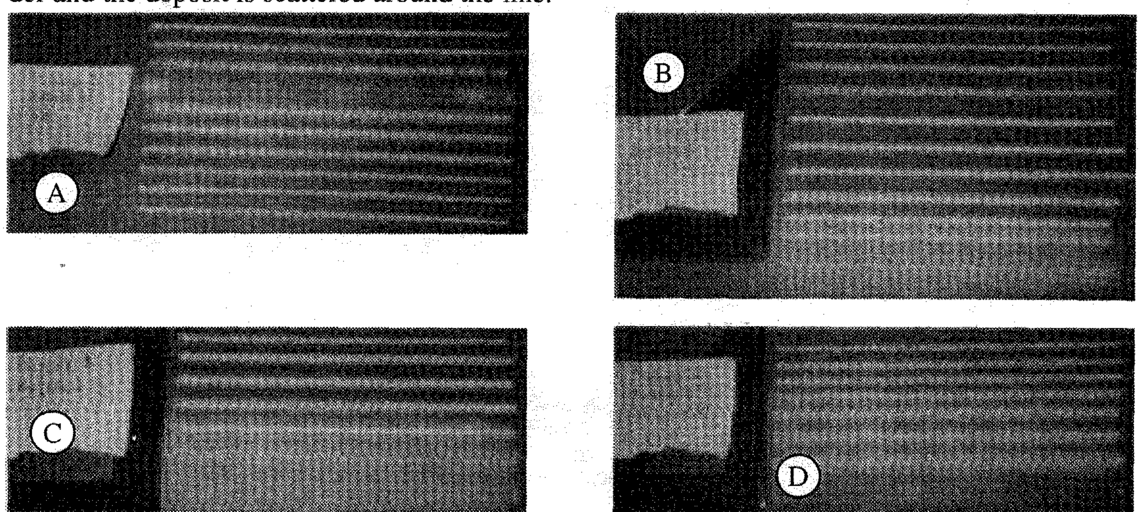


FIGURE 19. Sample deposition lines of ø220μm spherical glass beads on 120 grit sandpaper. Listed below are frequency and amplitudes, from top to bottom. Average position of the nozzle opening is 2-3mm above the substrate.

Figure (A): (30Hz, 31μm), (41Hz, 43μm), (41Hz, 48μm), (52Hz, 42μm), (52Hz, 38μm), (52Hz, 35μm), (52Hz, 31μm), (52Hz, 29μm).

Figure (B): (80Hz, 18μm), (80Hz, 18μm), (80Hz, 19μm), (80Hz, 23μm), (80Hz, 4μm), (80Hz, 4μm), (80Hz, 5μm), (80Hz, 6μm), (80Hz, 5μm), (80Hz, 6μm), (80Hz, 7μm).

Figure (C): (30Hz, 62μm), (30Hz, 105μm), (30Hz, 71μm), (30Hz, 76μm), (30Hz, 84μm), (30Hz, 96μm), (30Hz, 107μm).

Figure (D): (60Hz, 27μm), (60Hz, 32μm), (60Hz, 33μm), (60Hz, 36μm), (60Hz, 38μm), (60Hz, 42μm), (60Hz, 47μm).

Part B of Figure 19 however, appear to contradict this simple view of the deposition mechanics. Indeed at 80Hz, the quality of the deposit deteriorates rapidly between 4 and 7μm amplitude, to be restored between 18 and 23μm. At this time, we do not have any analytic interpretation for the cause of this singular behavior.

Despite the lack of an analytical model of the deposition process, the experiments described herein did identify the process parameters influencing the deposit geometry. They are listed below in Table 2.

TABLE 2. Process parameters affecting the deposit geometry.

FLOW CONTROL PROCESS PARAMETERS			
POWDERS			
Size	Geometry	Material/Density	Hygrometry
DOWNCOMER			
Size of opening		Angle of opening	
VIBRATIONS			
Amplitude	Frequency	Waveform	
SUBSTRATE			
Material	Energy Absorption	Roughness	

Multiple Powder Deposition. We conclude this section with a brief note on the process of greatest interest to layered manufacturing. The pattern deposited in Figure 20 points to the feasibility of multi-material deposition. This layer was generated by the juxtaposition of type I Portland cement and ø220μm spherical glass beads in a single layer.

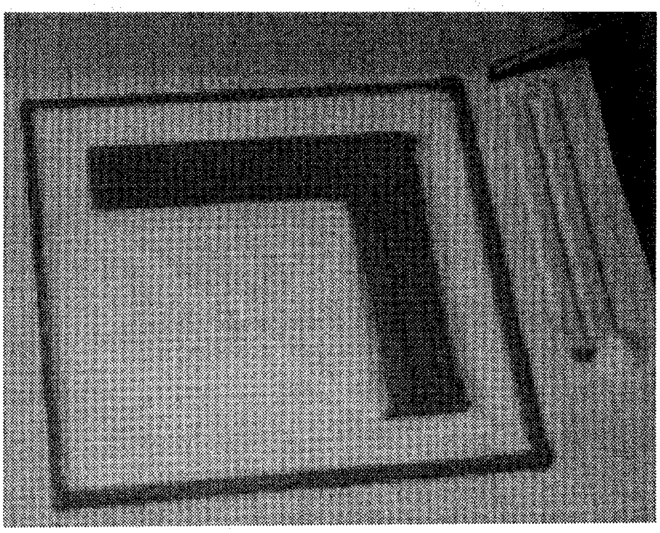


FIGURE 20. Sample two-powder deposition: Type I Portland Cement and 220μm spherical glass beads.

6 CONCLUSION

Layered manufacturing processes based on selective aggregation of powders (E.g: SLS, 3D Printing) all rely on blanket deposition of the build material. This geometric constraint severely limits the prospect of expansion into multi-material and functional materials of an otherwise well developed technology.

This paper introduces the Sand-Painter project. It derives from the ancestral art by the same name, which consist of decorating a flat substrate by depositing colored sand patterns. The present article focuses on reporting the results of an experimental design approach to the Sand-Painting process. Investigations reported herein focus on the experimental characterization of powder flows though the downcomer of a vibrationally actuated hopper and its corresponding deposition characteristics. The results to date validate the Sand-Painter concept. The results to date though, are insufficient for an analytical characterization of the process. Yet, they establish a methodology and approach, which can open selective aggregation processes to the realm of multi-material structures.

7 Acknowledgments

The project presented in this paper is above all an exercise in shoestring research and scavenging. It owes much to the cooperation of the Mechanical Engineering Department at Concordia University, the Concordia Center for Advanced Vehicle Engineering (CONCAVE), and above all it owes a debt of gratitude to the undergraduate students involved. The Mechanical Engineering Department provided the computer, data acquisition, and CNC. CONCAVE provided the shaker. The undergraduate research assistant acknowledged as co-authors provided their resourcefulness, energy and commitment.

Partial funding for this project was provided by the Natural Science and Engineering Research Council (NSERC) of Canada, and by the Concordia University Faculty Research and Development Program. All contributors are gratefully acknowledged.

8 References

[Pegna, 1995a] "Application of Cementitious Bulk Materials to Site Processed Solid Freeform Construction," Proceedings of the Solid Freeform Fabrication Symposium, Ed. by H.L Marcus, J.J. Beaman, D.L. Bourell, Joel W. Barlow, and R. H. Crawford, Austin, Tx, August 1995, pp.39-45.

[Pegna, 1995b] "Exploratory Investigation Of Layered Fabrication Applied To Construction Automation," Proceedings of the ASME Design Technical Conferences, Design Automation Conference, Sept. 17-21, 1995, Boston, Ma., DE-Vol. 82, pp.219-226.

[Pegna, 1997] "Exploratory Investigation of Solid Freeform Construction," *Automation in Construction*, Vol. 5, no.5, pp. 427-437 (Mar. 97)

[Rock and Gilman, 1995] "A New SFF Process for Functional Part Rapid Prototyping and Manufacturing: Freeform Powder Molding", Proceedings of the Solid Freeform Fabrication Symposium, Ed. by H.L Marcus, J.J. Beaman, D.L. Bourell, Joel W. Barlow, and R. H. Crawford, Austin, Tx, August 1995, pp.80-87.

[Sachs et al., 1990] Sachs, E., Cima, M., Cornie, J.; *"Three Dimensional Printing: Rapid Tooling and Prototypes Directly for a CAD Model,"* Annals of CIRP, Vol.39, 1, pp. 201-204 (1990)

[Deckard and Beaman, 1987] "Solid Freeform Fabrication and Selective Laser Sintering" Proceedings of the 15th NAMRC-SME, (1987)

[Brown and Richards, 1982] Principles of Powder Mechanics, Pergamon Press, 2nd ed. (1987)

[Mason and Woodcock, 1987] Bulk Solids Handling, Leonard Hill, N.Y., 1987

[Hans, 1990] Particle Technology, Chapman And Hall, N.Y. 1990

[Taguchi, 1987] System of Experimental Design I & II, UNIPUB Kraus International Publications (1987).