Application of Cementitious Bulk Materials to Site Processed Solid Freeform Construction

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Abstract: *This paper reports a radical departure from generally accepted concepts in construction automation and demonstrates that new techniques of layered manufacturing can be applied effectively to construction. In the process, we also modified material processing of cement to adapt it to the requirements of Solid Freeform Fabrication.*

Our purpose is illustrated with sample structures manufactured by incremental deposition of reactive bulk materials (cement and Silica in this instance), a characterization of their material properties, and an assessment of their potential for Solid Freeform Fabrication of large structures. For example, we estimated that it would take about 2.5 months to build a structure the size of a 3000 sq. ft. house.

Keywords: *Selective aggregation, Large structures, Functional Prototypes, Multimodal structures, Construction Automation.*

1 Classification of Additive Manufacturing Processes

Additive manufacturing processes are a recent addition to the engineer's arsenal. They result from a fundamental paradigm shift in manufacturing technology. Additive processes build-up a part in small organized increments rather than carving it out of a blank, as has been customary for centuries. This new approach provides the designer not only with a tool for rapid prototyping and tooling, but with the opportunity to obtain functional parts and systems that are inconceivable by other means. Ideally, one would like to obtain systems that are multimodal in terms of build material, with arbitrary topologies, and that can customize material to the intended function of the design.

The fundamental principles involved in Additive Manufacturing Processes demand that solid material be added incrementally and eventually grown or assembled into the desired shape and material composition. The first dimension of this problem is geometric in nature depending upon the scanning technique used for building up the part. The desired incremental geometry can be obtained by either sweeping a point, a line or a surface. The second dimension of the problem is material transport to the deposition area. Material can be transported in gas or liquid form and selectively subjected to a change of phase; or it can be transported in solid phase and selectively

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aggregated. All additive manufacturing processes can be characterized by their geometric and transport attributes as summarized in Tables 1 and 2.

Our research program is concerned with the fundamental principles of additive manufacturing processes. It seeks to achieve a process capable of providing not only geometry but also customize material properties within a generic environment. In view of the Rapid Prototyping/Solid Freeform Fabrication literature, it is possible to attain fine control over the nature and properties of the deposit obtained by selective change of phase (See [Maxwell et al., 1995] for example.) We conjecture however that control of the material nature and microstructure limits admissible flow rates to about $10^8 \mu m^3/s$. Beyond that rate, it appears that most researchers assume that additive manufacturing processes by selective change of phase are material specific. Hence specific processes have been developed for specific materials (stereolitography for example.)

The most likely route to additive manufacturing for large parts —while retaining some material flexibility— is selective aggregation of powders. Selective laser sintering, for example, has already been shown to apply to various polymer, ceramics and metal powders. The resulting structure however is a porous aggregate with inhomogeneous properties.

2 Motivation and Background

Insofar, Solid Freeform Fabrication has proved useful in the rapid fabrication of visual prototypes and tooling. As the technology develops, it is now aiming at producing functional parts and systems. In this natural evolution of technology, parts are still limited in size to a few decimeters for non-functional prototypes and a few centimeters for functional ones. Can one process deliver functional prototypes of meter size and above? This is the challenge addressed by this project. It's eventual aim is to investigate the use of layered manufacturing as a potential approach to Construction Automation.

Indeed, construction may very well be the single most difficult challenge to manufacturing automation. Construction is essentially a prototype fabrication, and has so far resisted most attempts at automation. Other manufacturing sectors have seen their productivity increase many

TABLE 1. Classification of Additive Manufacturing Processes by Selective Change of Phase

Sweep Geometry	Transport: Gas Phase	Transport: Liquid Phase
Point	•LCVD •SALD	•LLCVD •Stereolithography
Line	•Photolytic LCVD of lines.	•None
Surface	•Blanket LCVD	•Cubital™ •Light Sculpting™ •Mask Electroplating

TABLE 2. Classification of Additive Manufacturing Processes by Selective Aggregation

Binder Activation/Deposition	Deposition: Point	Deposition: Line	Deposition: Surface
Point	•Ballistic Particle Manufacturing. •Sanders Prototyping Inc.™ •Shape Melting.	•Fused Deposition Manufacturing.	•3-D Printing. •Selective Laser Sintering.
Line	•None.	•None.	•None.
Surface	•Selective Aggregation of Reactive Bulk Material (Presented in this paper)	•Filament Winding.	•Composite Prepreg Fabrication. •Laminated Object Manufacturing. •Spray Deposition.

times over when they became automated. The last 10 years of extensive experiments in construction robotics however, have yielded little or no productivity improvement [Kajioka et al., 1990].

The reasons for this apparent paradox is discussed in [Pegna, 1995]. In a nutshell, we claim that it is due mostly to the prototyping aspect of construction, and in part to an inefficient use of materials. In most instances, robotics research has only sought to duplicate human labor without questioning the process in the first place. As a result, research has lead to islands of automation with ever larger machines intended to assemble ever larger structures. Related but not negligeable is the inefficient use of material. The insane amount of solid waste generated by the construction industry may contribute as much as 23% of the national stream [Apotheker, 1990].

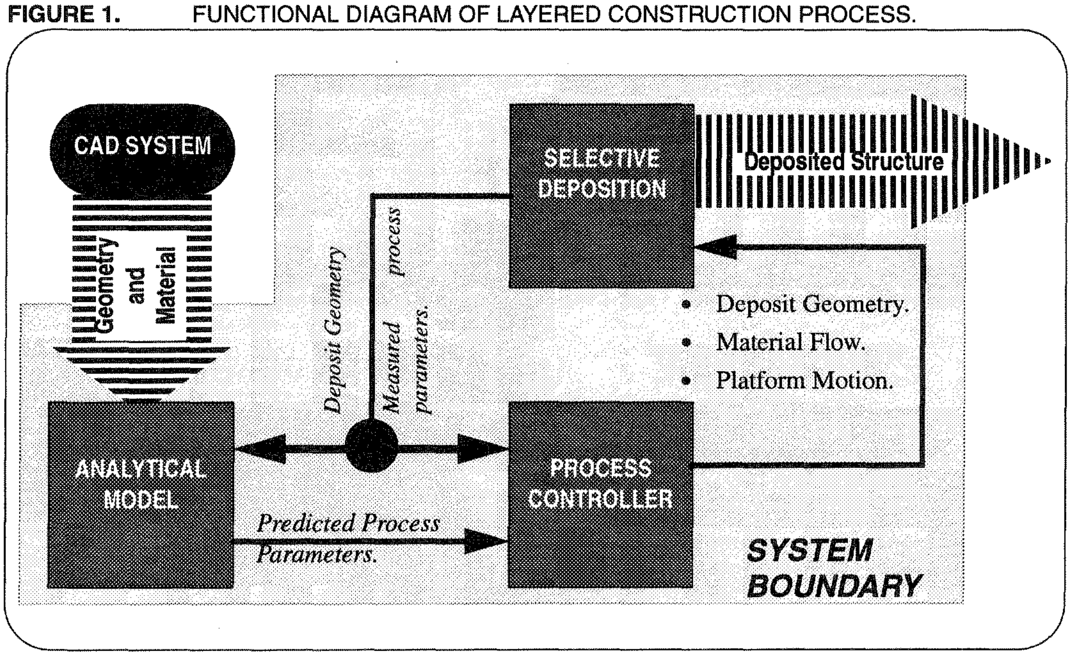
In view of the similarities between construction and solid freeform fabrication, our research has taken the opposite route. Instead of giant machines assembling giant parts, a large structure could conceivably be built by an army of ants, one grain of sand at a time.

3 EXPERIMENTAL PROCESS

As pointed out in Section 1, selective aggregation of bulk solid material appears to be the most likely technique capable of achieving parts of meter size and over. Selective aggregation can be effected in the following manners: Selective deposition of an activated binder into the bulk material, as in the 3-D Printing process [Sachs et al., 1990]; selective activation of a passive binder present in the bulk material —including self-cementing materials— as in the Selective Laser Sintering Process [Deckard et al., 1987]; or activation of a binder selectively deposited into the bulk material. The latter was chosen as it is also the most flexible in permitting fabrication from a very wide range of bulk materials in various forms (powder, pebbles, or blocks for example.)

As is now customary in Solid Freeform Fabrication, the basic principle of operation is to incrementally build-up layers of the structure. The geometry of each layer is obtained directly

FIGURE 1. FUNCTIONAL DIAGRAM OF LAYERED CONSTRUCTION PROCESS.



from slicing a geometric model and is translated into scanning motion of the end-effector. This process is illustrated by the diagram in Figure 1 and was adopted for this project.

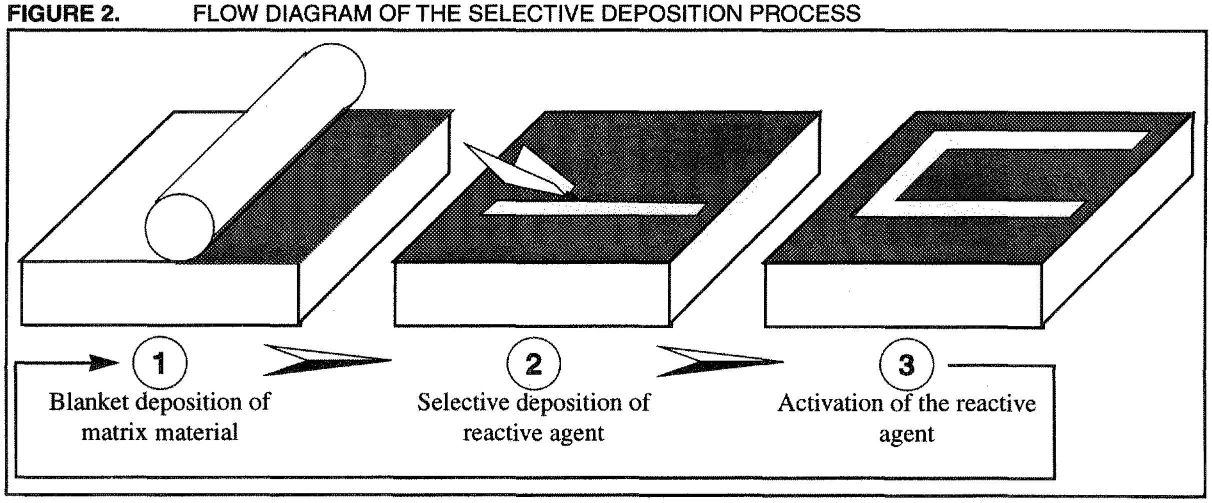
The core of the process involves selective deposition of a powdered binder material onto a bed of powdered matrix material. From a material handling perspective, this technique is akin to the age old tradition of sand painting practiced for centuries by Navajo Indians and Tibetan Monks. The resulting mix is then activated by a catalyst (in this case water). The process is illustrated by Figure 2.

For lack of funds, the approach of automated deposition suggested in Figure 2 was not implemented. Instead, masking processes were combined with uniform deposition of matrix and binder to achieve the desired result. The masks were obtained by slicing the geometry and plotting the outer and inner layer boundaries on two different masks. The two masks were used in combination to sift the binder material and then removed leaving only the exposed cross-section impregnated with binder. The process steps are illustrated in Figure 3.

The material used for this experiment were sand and Portland Cement. A series of sample hollow concrete structures 3"x3"x6" was fabricated in layers. The geometry of the sample is shown in Figure 4. Note that this structure could not be produced by regular concrete casting techniques. Various tests were conducted with and without compressing the granular sand and cement layer. Various sand to cement ratios were experimented with. Wetting of the layer was initially performed by spray mist of liquid water onto each layer as it was completed and cured. It was found that this approach led to brittle samples. When observed under the microscope, it was seen that cement had formed large aggregates and had not bonded with sand. Regardless of the sand to cement and water ratios, the concrete structure had cracks running along the layer structures. This phenomenon is attributed to the effect of surface tension in the deposited droplets of liquid water.

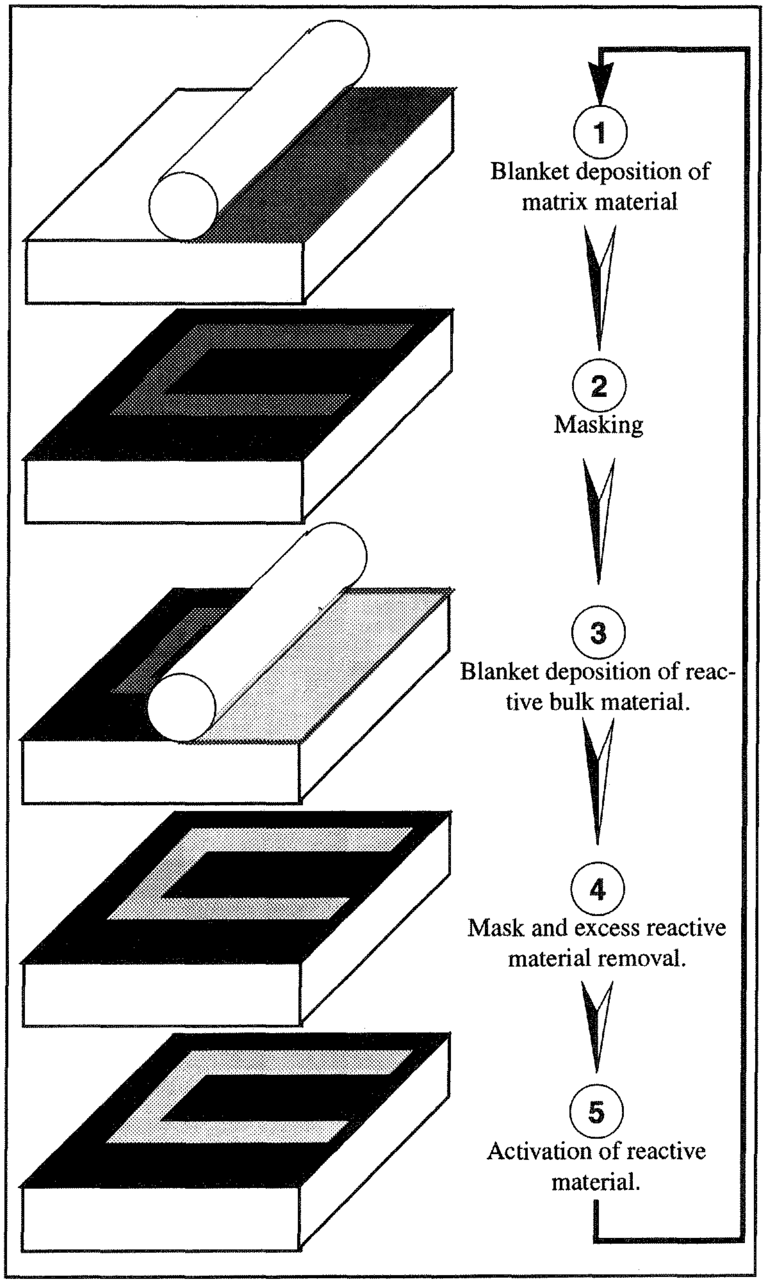
Excellent bonding was obtained however when steam was used in place of water. After all layers were completed, the sample was placed into a pressurized steam chamber. The pressure and temperature in the chamber were respectively 3 atmospheres and 300°C and caused the concrete to cure rapidly. When observed under a microscope, the layers were so well bonded that it was

FIGURE 2. FLOW DIAGRAM OF THE SELECTIVE DEPOSITION PROCESS



impossible to tell them apart. The concrete obtained by this method is dense and has no apparent porosity or cracks. Vibration tests were also conducted using a bench designed for testing electronic equipment at Teledyne Corporation. These vibration tests, which destroyed all the water sprayed samples, failed to break the steamed samples. Later, tests were conducted applying vapor at atmospheric pressure in between each layers and gave similar results. A picture of the part is shown in Figure 5.

FIGURE 3. FLOW DIAGRAM OF THE SELECTIVE DEPOSITION PROCESS



The choice of materials used in this experiment was justified by cost considerations alone. Indeed the proposed process is essentially about selective deposition of powders that either react together when exposed to a catalyst (localized heat, electric current) or a chemical (water in this case.)

4 MATERIAL CHARACTERIZATION

This material was not available in time for publication of this paper and will be presented at the symposium.

5 TECHNOLOGY ASSESSMENT

Many construction processes qualify as additive manufacturing. This is what may have caused the demise of robotics since the part and the robot's environment are one and the same. Manufacturing automation usually assumes a constant environment —e.g. plant or workcell— and changing parts but it does lack sensor and information processing capable of dealing reliably with a changing environment. This is where solid freeform fabrication has a definite advantage over robotics. Indeed, in SFF, the part is incrementally built in an organized manner. We claim that this attribute makes SFF ideally suited for off-site as well as on-site construction.

FIGURE 4. SAMPLE TEST PART SPECIFICATIONS

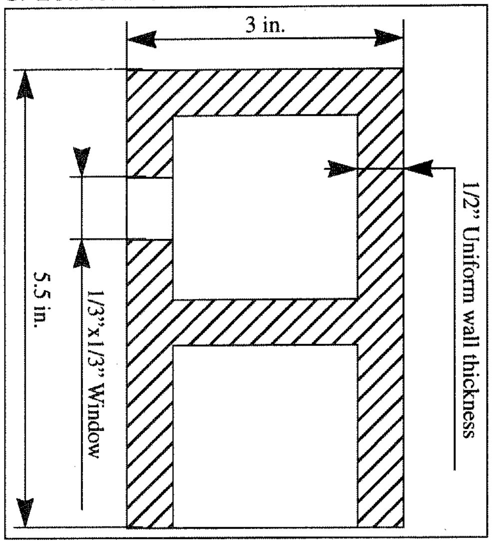
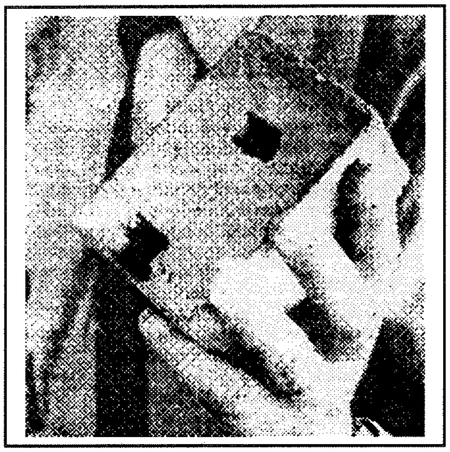


FIGURE 5. SAMPLE HO SCALE BLOCK-HOUSE PRODUCED BY LAYERED MANUFACTURING OF STEAMED CEMENT-SILICA



5.1 Rapid Prototyping of Large Functional Structures and Off-Site Construction

Solid Freeform Fabrication has already spun off number of successful applications in rapid prototyping, rapid tooling and mold making. To be useful for large parts and off-site construction of large functional structures, however the process must reach volumetric flowrates that make SFF economically viable.

Attempts are underway at scaling up existing processes to produce large scale prototypes with characteristic sizes of a meter and above. However, current SFF technology hits a technological barrier when it comes to increasing the volumetric flow rate of build material.

As per the classification presented in Section 2, the maximum volumetric flow rate is obtained when the build material is already in bulk solid form, leaving selective aggregation as the only viable alternative for large parts. Another aspect of the same problem is the delivery of binder. Binder material should deposited at a rate that satisfies both the build flow rate and the geometric accuracy requirements. Our process achieves this result with deposition of the binder in powder form, leaving activation as a blanket process.

5.2 On-Site Construction Automation

We argues that layered fabrication is a viable approach to on-site automated construction. In a first phase, our technology is expected to be applicable to the automated construction of simple on-site structures such as catch basin, foundations, and decks.

As the technology develops, it may also become a viable commercial alternative to lumber construction. Because this technology offers on-site construction automation, it would reduce the dependence upon labor, the risk of injuries, and weather stoppage. A rough estimate is that this technology may cut construction cost by about 30%.

An advantage of the proposed approach to construction automation is its environmental benefits. A large body of work has demonstrated the effectiveness of using waste material, such as fly ash as a construction material [Goumans et al., 1994]. Our general purpose material handling approach makes using such materials a viable alternative in the process. A further benefit of SFF is its thrifty use of material. Indeed, all unused material can be readily recycled, contributing to a significant waste reduction in construction.

6 Conclusion

Proof of concept for a new process aimed at solid freeform fabrication of large (> 1meter) structures was performed. In this paper, we presented a characterization of additive manufacturing processes and argued that selective aggregation was the only technique prone to fabrication of large scale structures. To prove the point, a novel system of layered fabrication was studied. It involved depositing a layer of reactive material (Portland cement) over a layer of matrix material (silica). Two methods were proposed to perform the task of binding the cross-sectional material: (1) the binder is selectively deposited and blanket activated, or (2) the binder is blanket deposited and selectively activated. Parts were built out of sand (matrix) and Portland cement (reactive material) activated by water vapor. The resulting structure is denser than, and exhibits mechanical properties similar to cast concrete.

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