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Automated construction by contour crafting—related robotics and information technologies

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Abstract

Although automation has advanced in manufacturing, the growth of automation in construction has been slow. Conventional methods of manufacturing automation do not lend themselves to construction of large structures with internal features. This may explain the slow rate of growth in construction automation. Contour crafting (CC) is a recent layered fabrication technology that has a great potential in automated construction of whole structures as well as subcomponents. Using this process, a single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run, imbedded in each house all the conduits for electrical, plumbing and air-conditioning. Our research also addresses the application of CC in building habitats on other planets. CC will most probably be one of the very few feasible approaches for building structures on other planets, such as Moon and Mars, which are being targeted for human colonization before the end of the new century.

Keywords: Contour crafting; Housing construction; Construction information technology; Construction on other planets

1. Introduction

Since the early years of the 20th century, automation has grown and prevailed in almost all production domains other than construction of civil structures. Implementation of automation in the construction domain has been slow due to: (a) unsuitability of the available automated fabrication technologies for large scale products, (b) conventional design approaches that are not suitable for automation, (c) significantly smaller ratio of production quantity/type of final products as compared with other industries, (d) limitations in the materials that could be employed by an automated system, (e) economic unattractiveness of expensive automated equipment and (f) managerial issues. On the other hand, the following are reported to be serious problems that the construction industry is facing today [1]:

- labor efficiency is alarmingly low,
- accident rate at construction sites is high,
- work quality is low and
- control of the construction site is insufficient and difficult, and skilled workforce is vanishing.

Automation of various parts and products has evolved considerably in the last two centuries but with the exception of a few successful attempts (see for example [2]) construction of whole structures remains largely as a manual practice. This is because

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the various conventional methods of manufacturing automation do not lend themselves to construction of large structures. A promising new automation approach is layered fabrication, generally known as rapid prototyping (RP) or solid free-form fabrication (SFF). Although several methods of rapid prototyping have been developed in the last two decades [3], and successful applications of these methods have been reported in a large variety of domains (including industrial tooling, medical, toy making, etc.), most current layered fabrication methods are limited by their ability to deliver a wide variety of materials applicable to construction. Additionally, they are severely constrained by the low rates of material deposition which makes them attractive only to the fabrication of small industrial parts. Currently, contour crafting (CC) seems to be the only layer fabrication technology that is uniquely applicable to construction of large structures such as houses [5].

2. Contour crafting

CC is an additive fabrication technology that uses computer control to exploit the superior surface-forming capability of troweling to create smooth and accurate planar and free-form surfaces [6–8]. Some of the important advantages of CC compared with other layered fabrication processes are better surface quality, higher fabrication speed and a wider choice of materials.

The key feature of CC is the use of two trowels, which in effect act as two solid planar surfaces, to create surfaces on the object being fabricated that are exceptionally smooth and accurate. Artists and craftsmen have effectively used simple tools such as trowels, blades, sculpturing knives, and putty knives, shown in Fig. 1, with one or two planar surfaces for forming materials in paste form since ancient times. Their versatility and effectiveness for fabricating complex free-form as well as planar surfaces is evidenced by ancient ceramic containers and sculptures with intricate or complex surface geometries as well as detailed plaster work that have shapes as complicated as flowers, on the walls of rooms. Surface shaping knives are used today for industrial model making (e.g., for building clay models of car bodies). However, despite the progress in process mechanization with computer numerical control and robotics, the method of using these simple but powerful tools is still manual, and their use is limited to model building and plaster work in construction.

Fig. 1. Simple historical construction tools.

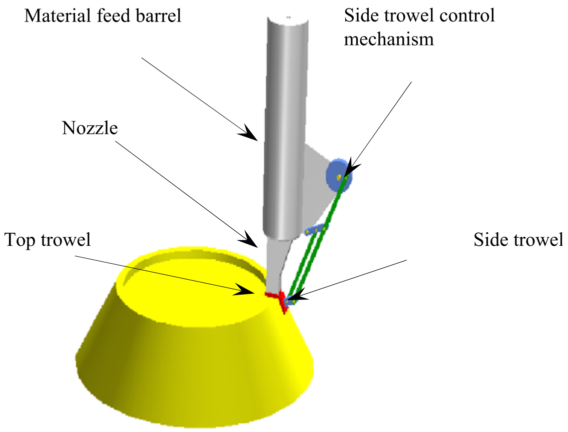

Fig. 2. Contour crafting process.

In CC, computer control is used to take advantage of the superior surface forming capability of troweling to create smooth and accurate, planar and free-form surfaces. The layering approach enables the creation of various surface shapes using fewer different troweling tools than in traditional plaster handwork and sculpting. It is a hybrid method that combines an extrusion process for forming the object surfaces and a filling process (pouring or injection) to build the object core. As shown in Fig. 2, the extrusion nozzle has a top and a side trowel. As the material is extruded, the traversal of the trowels creates smooth outer and top surfaces on the layer. The side trowel can be deflected to create non-orthogonal surfaces. The extrusion process builds only the outside edges (rims) of each layer of the object. After complete extrusion of each closed section of a given layer, if needed filler material such as concrete can be poured to fill the area defined by the extruded rims.

3. Application in construction

Application of CC in building construction is depicted in Fig. 3 where a gantry system carrying the nozzle moves on two parallel lanes installed at the construction site. A single house or a colony of houses, each with possibly a different design, may be automatically constructed in a single run. Conventional structures can be built by integrating the CC machine with a support beam picking and positioning arm, and adobe structures, such as the ones designed by CalEarth (www.calearth.org) and depicted in the Fig. 4, may be built without external support elements using shape features such as domes and vaults. Following are some interesting aspects of this automated construction concept.

3.1. Design flexibility

The process allows architects to design structures with functional and exotic architectural geometries that are difficult to realize using the current manual construction practice.

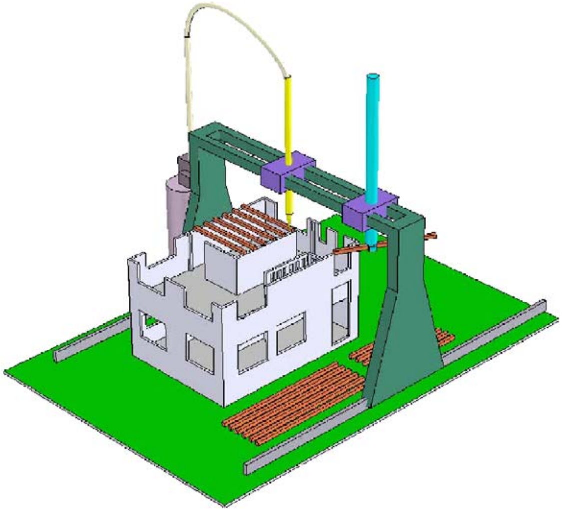

Fig. 3. Construction of conventional buildings using CC.

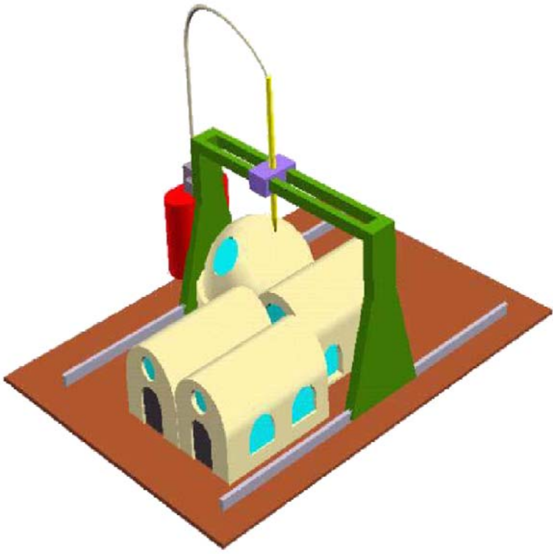

Fig. 4. Construction of adobe buildings using CC.

3.2. Multiple materials

Various materials for outside surfaces and as fillers between surfaces may be used in CC. Also, multiple materials that chemically react with one another may be fed through the CC nozzle system and mixed in the nozzle barrel immediately before deposition. The quantity of each material may be controlled by computer and correlated to various regions of the geometry of the structure being built. This will make possible the construction of structures that contain varying amounts of different compounds in different regions.

3.3. Utility conduits

As shown in Fig. 5, utility conduits may be built into the walls of a building structure precisely as dictated by the CAD data. Sample sections made with CC and filled with concrete as shown in Fig. 8 demonstrate this possibility.

3.4. Paint-ready surfaces

The quality of surface finish in CC is controlled by the trowel surface and is independent of the size of the

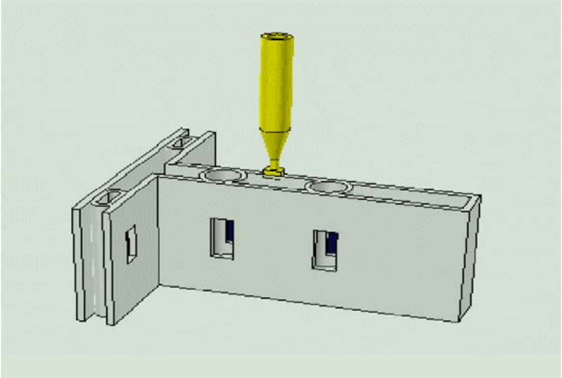

Fig. 5. Complex wall section.

nozzle orifice. Consequently, various additives such as sand, gravel, reinforcement fiber and other applicable materials available locally may be mixed and extruded through the CC nozzle. Regardless of the choice of materials, the surface quality in CC is such that no further surface preparation would be needed for painting surfaces. Indeed, an automated painting system may be integrated with CC.

3.5. Smart materials

Since deposition in CC is controlled by computer, accurate amounts of selected construction materials, such as smart concrete, may be deposited precisely in the intended locations. This way the electric resistance, for example, of a carbon filled concrete may be accurately set as dictated by the design. Elements such as strain sensors, floor and wall heaters can be built into the structure in an integrated and fully automated manner.

3.6. Automated reinforcement

Robotic modular imbedding of steel mesh reinforcement into each layer may be devised, as shown in Fig. 6. The three simple modular components shown in this figure may be delivered by an automated feeding system that deposits and assembles them between the two rims of each layer of walls built by CC. A three-dimensional mesh may be similarly built for columns. Concrete may then be poured after the rims of the wall or column are built by CC. The mesh can follow the geometry of the structure. Note that in this configuration the CC nozzle, the steel reinforcement module feeder, and the concrete filler feeder could all be on the same gantry system. Such a system can create shapes with smooth outer surfaces and reinforced internal structure automatically and in one setup.

As an alternative to traditional metal reinforcement, other advanced materials can be used, such as

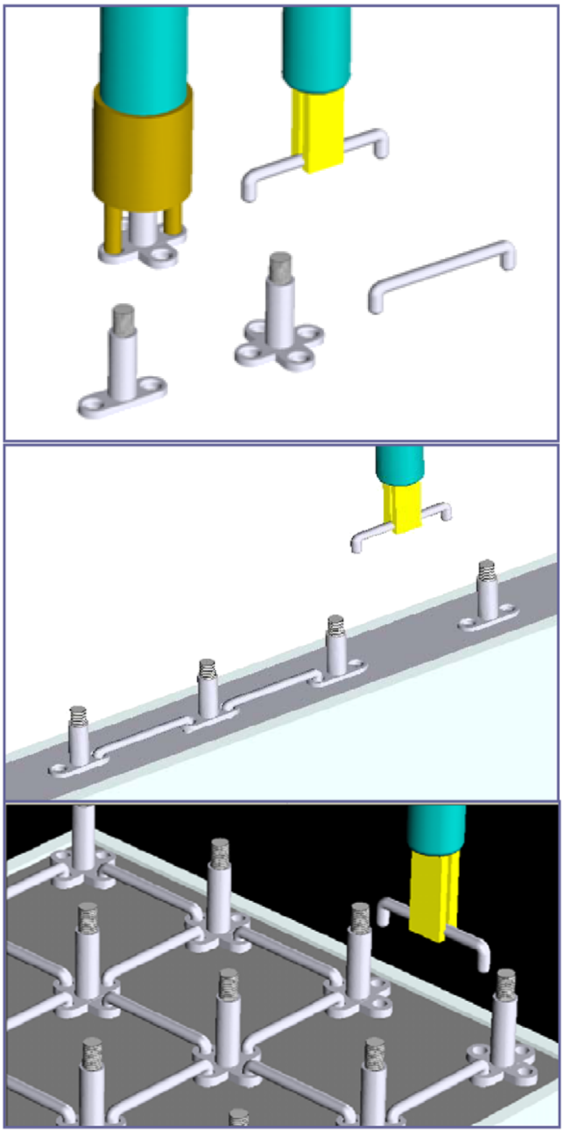

Fig. 6. Reinforcement components and assembly procedures for walls and columns.

the fiber reinforced plastics (FRP). Since the nozzle orifice in CC does not need to be very small, it is possible to feed glass or carbon fiber tows through the CC nozzle to form continuous reinforcement consolidated with the matrix materials to be deposited. In the proposed study, deposition of the FRP reinforcement by a parallel nozzle built into the CC nozzle assembly will also be considered. Co-extrusion is further discussed in a later section.

Reinforcement can also be provided using the post-tensioning system. Accurate ducts can be generated by the CC process. Similar to post-tensioned concrete construction, metal or FRP wires can be fed through the ducts and then post-tensioned to provide reinforcement.

3.7. Automated tiling of floors and walls

Automated tiling of floors and walls may be integrated by robotically delivering and spreading the material for adhesion of tiles to floors or walls, as shown in Fig. 7. Another robotic arm can then pick the tiles from a stack and accurately place them over the area treated with the adhesive material. These robotic arms may be installed on the same structure which moves the CC nozzle.

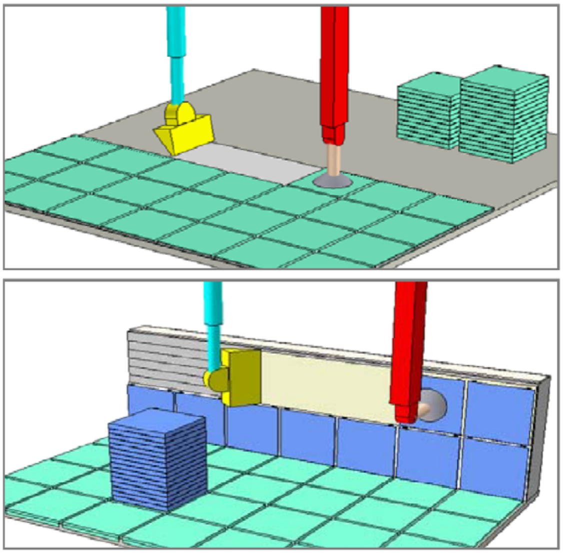

Fig. 7. Automated tiling.

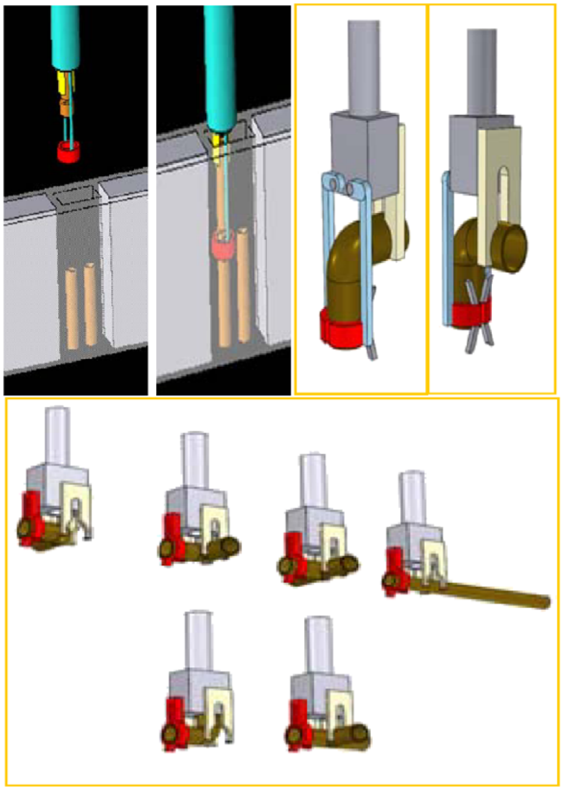

Fig. 8. Plumbing modules and grippers.

3.8. Automated plumbing

Because of its layer by layer fabrication method, a contour crafting based construction system has the potential to build utility conduits within walls. This makes automated construction of plumbing and electrical networks possible. For plumbing, after fabrication of several wall layers, a segment of copper (or other material) pipe is attached through the constructed conduit onto the lower segment already installed. The robotics system, shown on the upper left side of Fig. 8, delivers the new pipe segment and in case of copper pipes has a heater element (shown in red) in the form of a ring. The inside (or outside) rim of each pipe segment is pretreated with a layer of solder. The heater ring heats the connection area, melts the solder and, once the alignment is made, bonds the two pipe segments. Other universal passive (requiring no active opening or closing) robotic gripper and heater mechanism designs used for various plumbing components are also shown in Fig. 4. The needed components may be pre-arranged in a tray or magazine for easy pick up by the robotic assembly system. Using these components various plumbing networks may be automatically imbedded in the structure.

3.9. Automated electrical and communication line wiring

A modular approach similar to industrial bus-bars may be used for automating electrical and communication line wiring in the course of constructing the structure by contour crafting. The modules, as shown in Fig. 9, have conductive segments for power and communication lines imbedded in electrically non-conductive materials such as a polymer, and connect modularly, much like the case of plumbing. All modules are capable of being robotically fed and connected. A simple robotics gripper can perform the task of grabbing the component from a delivery tray or magazine and connecting it to the specified component already installed. The automated construction system could properly position the outside access modules behind the corresponding openings on the walls, as specified by the plan. The only manual part of the process is inserting fixtures through wall openings into the automatically constructed network.

3.10. Automated painting

During or after layer-wise construction of walls, a spray painting robotics manipulator attached to the CC main structure may paint each wall according to desired specifications. The painting mechanism may be a spray nozzle or an inkjet printer head (such as those used for printing large billboards). The latter mechanism makes painting wall paper or other desired patterns possible.

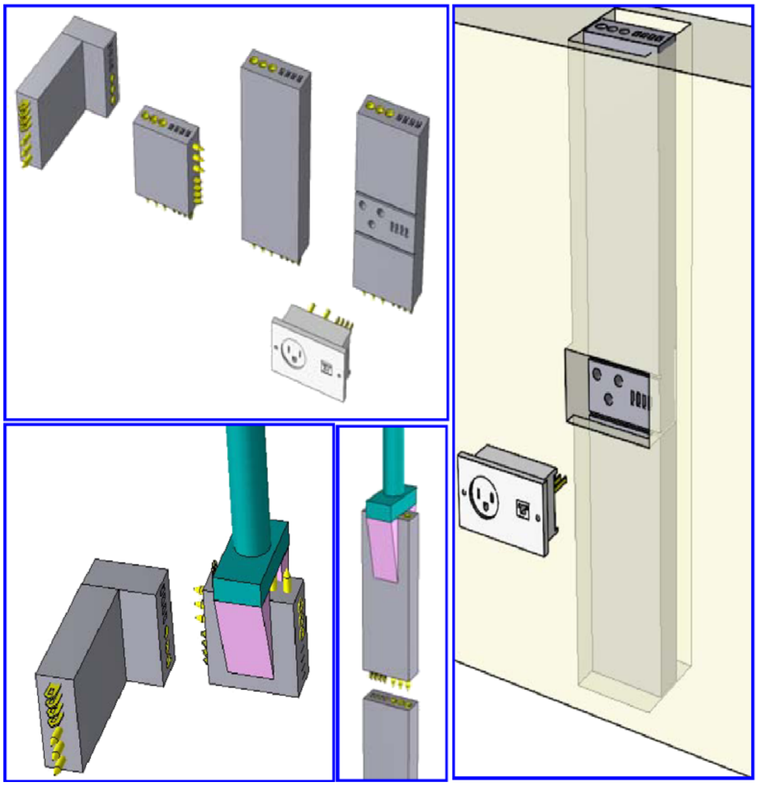

Fig. 9. Electrical modules and assembly process.

4. State of development

Several CC machines have been developed at USC for research on fabrication with various materials including thermoplastics, thermosets and various types of ceramics. These machine include a XYZ gantry system, a nozzle assembly with three motion control components (extrusion, rotation and trowel deflection) and a six-axis coordinated motion control system. The machine developed for ceramics processing is shown in Fig. 10 and is capable of extruding a wide variety of materials including clay and concrete. The material is extruded by means of a cylinder/piston system shown on the left side. The figure on the right shows the mechanism for nozzle rotation and side trowel deflection.

We have conducted extensive experiments to optimize the CC process to produce a variety of 2.5D and 3D parts with square, convex and concave features, some filled with concrete, as shown in Fig. 11. The scale has been of the samples made to date (the hand in Fig. 11 is indicative of the scale). Details of the related research may be found in [9] and [10].

4.1. Reinforcement

Towards improving the strength of large housing structures built through CC, we have investigated the use of a variety of reinforcements. For example, Fig. 12 shows pictures from our experiments with coil reinforcement. Owing to the high extrusion pressures prevailing in CC compared to other layered free-form fabrication techniques [11], the extrudate thoroughly adheres itself around the coils without causing any internal discontinuities. Similar results have been observed from our experiments with sand impregnation. Thus the use of reinforcements seems promising in our CC process.

4.2. Depositions with hollow cavities

Through extensive experimentation and a series of design enhancements, we have developed the capability to build layers with hollow depositions using CC as shown in Fig. 13. Mandrel of various shapes may be used for creating hollows of various shapes. Note that these hollow cavities result in lighter struc-

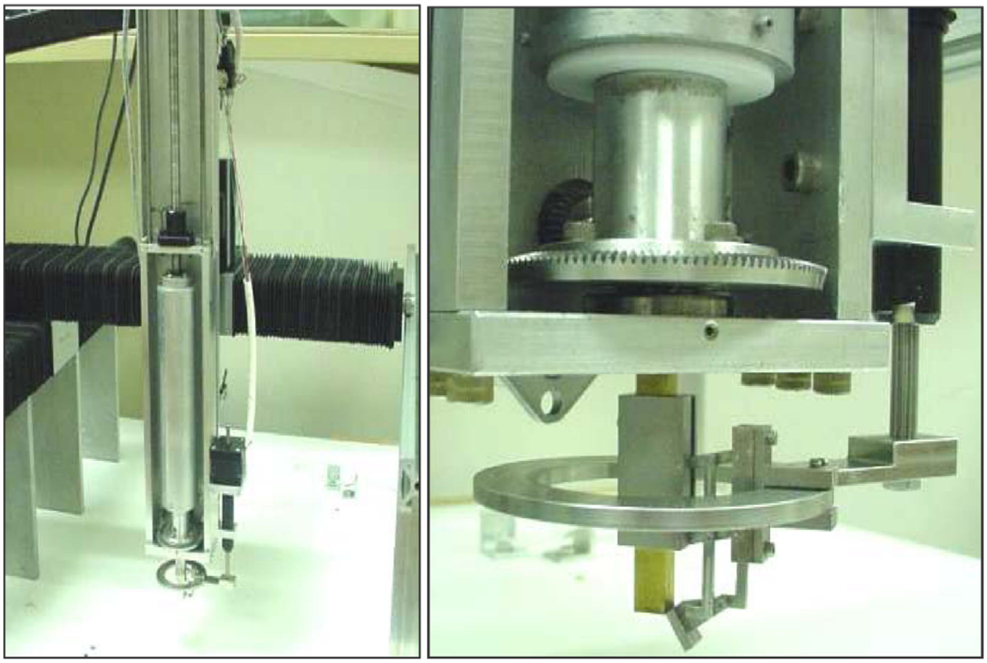

Fig. 10. The CC machine for ceramic paste extrusion.

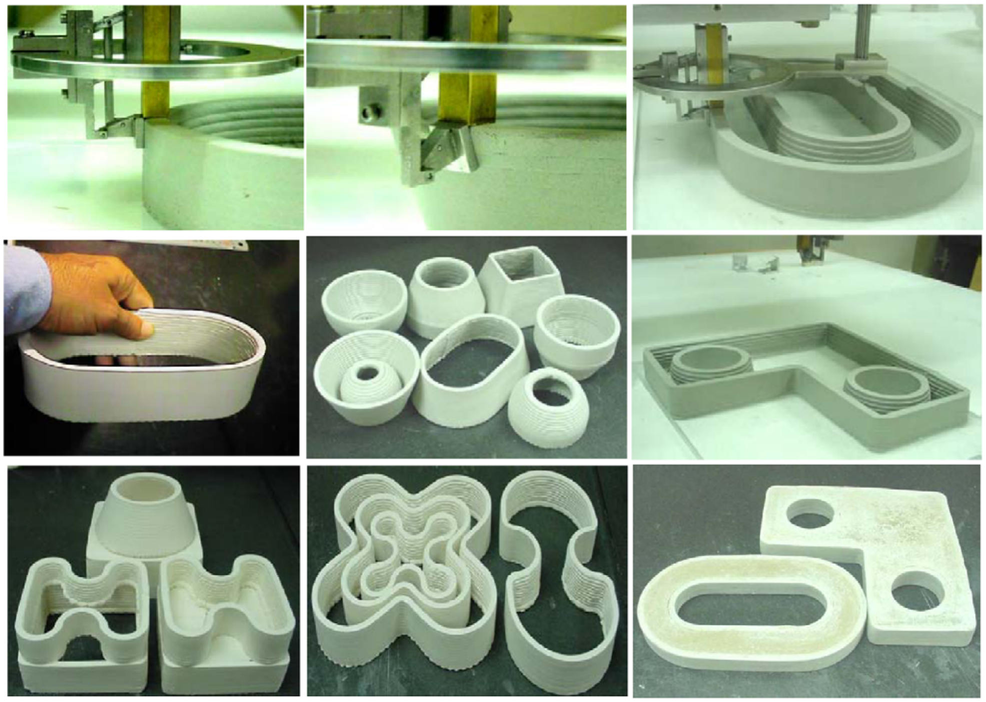

Fig. 11. CC in operation and representative 2.5D and 3D shapes and parts filled with concrete.

tures. It is also possible to extrude reinforcement materials, such as epoxies or various concrete based compounds through these cavities for added strength.

5. Future research plan

Under a new grant from the National Science Foundation, we are currently working on the development of new nozzle assemblies that are especially designed for full scale construction application. With the new nozzles, we intend to first fabricate full scale sections of various building features such as sections of walls with conduits built in, and supportless roofs and perform various structural analysis and testing using a wide variety of candidate materials. The new nozzle design, shown in Fig. 14, has the capability of full 6 axis positioning when mounted on a XYZ gantry

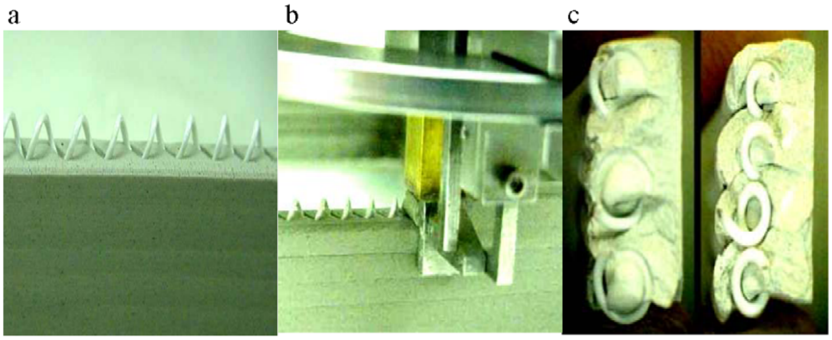

Fig. 12. Reinforcement process of CC: (a) metal coil placed on a top layer, (b) a fresh layer of extrudate covers the coil and (c) cross sections of the fabricated part with the reinforcement coil showing a reasonable adhesion between layers.

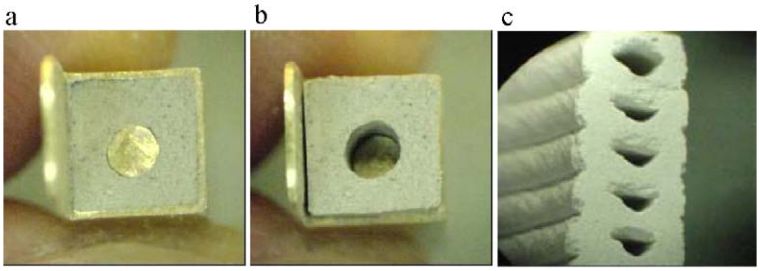

Fig. 13. Laying hollow sections through CC: (a) the ceramic material in the nozzle before extrusion, (b) hollow circle formed as the extrudate emerges from the orifice and (c) cross section of the fabricated part revealing the hollow sections.

system. and can co-extrude both outer sides and filler materials. The design incorporates rigid double-coaxial piped for material delivery. The nozzle design also conforms with concurrent embedding of steel reinforcement modules discussed earlier. This nozzle assembly will be capable of building a wide variety of curved structures as designed by architects. In devising our construction control software, we will benefit from the ancient body of knowledge that is currently being harnessed by CalEarth (see http://www.calearth.org) for building supportless closed structures. An example of a clever and ancient manual method of constructing such supportless structures is shown in Fig. 15 for construction of domes and vaults. Our corresponding deposition pattern, inspired by these ancient methods, could be such as the one schematically illustrated in

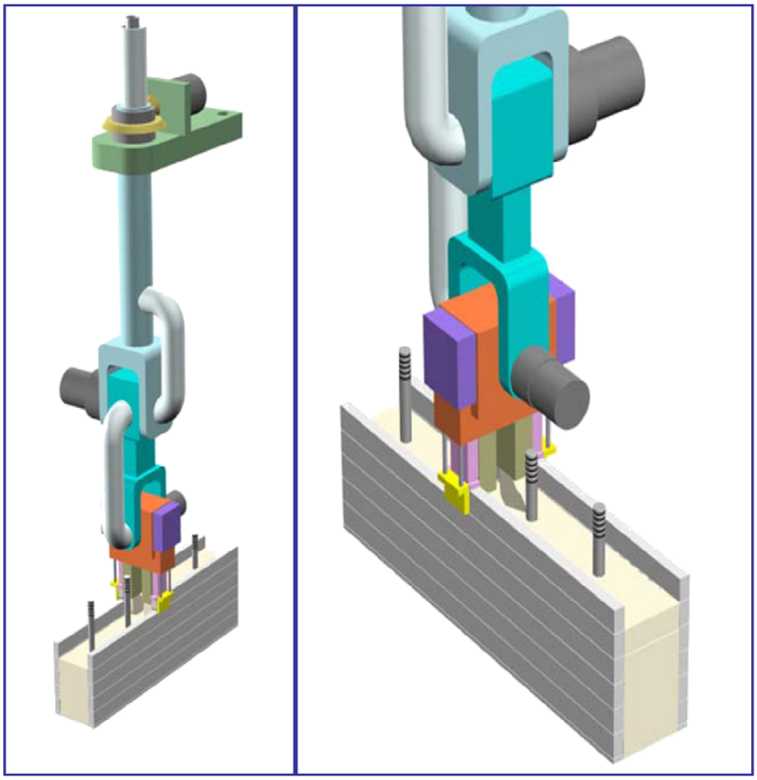

Fig. 14. Six axis nozzle design for concurrent rim and filler material delivery and conformance to reinforcement imbedding.

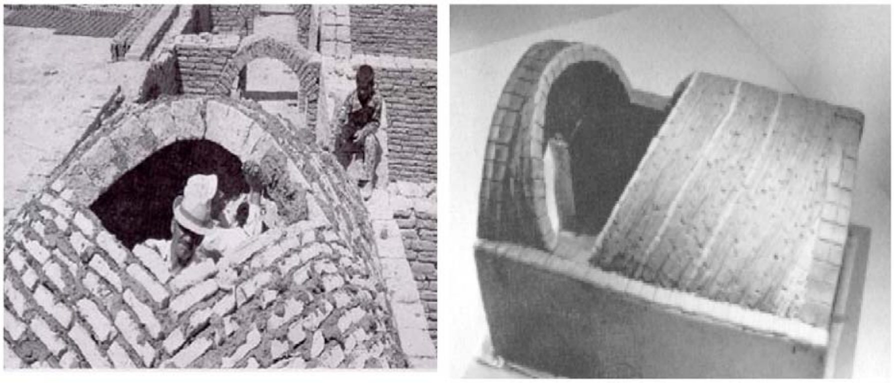

Fig. 15. Manual construction of adobe structures using bricks (source: Khalili, 2000 [4]).

Fig. 16 to be made possible with the new CC nozzle which provides the maximum positioning flexibility. We will analytically evaluate the performance characteristics of various deposition patterns and implement the most desirable approaches.

5.1. Alternative robotics approach

The process was depicted in Figs. 3 and 4 as using a gantry robot that has to be large enough to build an entire house within its operating envelope and lays one continuous bead for each layer. Such an approach is not without its attractions, but it requires a large amount of site preparation and a large robot structure. An approach involving the coordinated action of multiple mobile robots is to be preferred. The mobile robotics approach depicted in Fig. 17 has several advantages including ease of transportation and setup, the possibility of concurrent construction where multiple robots work on various sections of the structure to be constructed (as illustrated in Fig. 14), the possibility of scalable deployment (in number) of equipment and the possibility of construction of structures with unlimited foot print.

A construction mobile robot may use a conventional joint structure and be equipped with material tanks as well as material delivery pump and pipes. The end effector of the robot could carry a CC nozzle that can reach from ground level all the way to the top of a wall. If the mobile robot arm could be made of a rigid structure, position sensing at the end effector may not be necessary. Instead, a position sensor (e.g., a laser tracker) may be mounted at a fixed location, and the related retroreflectors may be installed on each mobile robot base. In this configuration, the robot does not engage in fabrication while moving. Once it reaches a pre defined post (called mobile platform post), it anchors itself by extending some solid rods

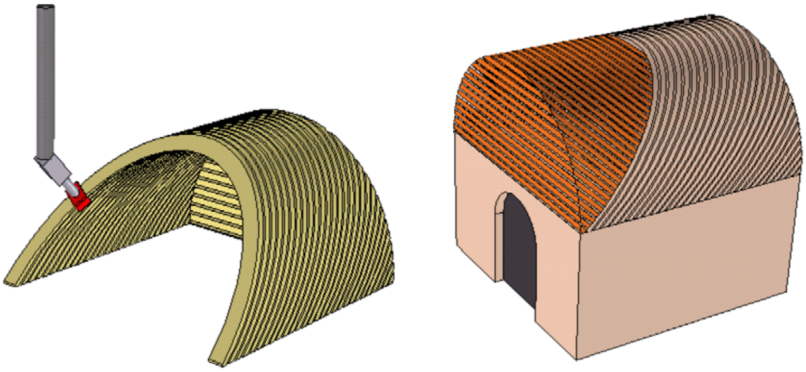

Fig.16. CC approach to fabricate supportless structures.

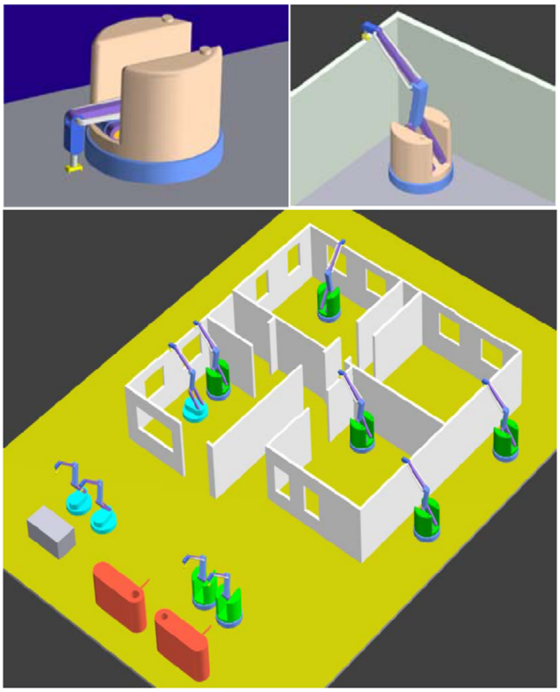

Fig. 17. Construction by mobile.

from its bottom. Then, it starts the fabrication from the last point fabricated while at the previous post. This arrangement is routinely practiced in some industrial applications such as robotic welding of large parts, such as in ship building.

Roof construction may or may not need support beams. Supportless structures such as domes and vaults may be built by mobile robots. For planar roofs, beams may be used. Under each beam a thin sheet may be attached. The beams may be picked and positioned on the structure by two robots working collaboratively, each being positioned on the opposite sides outside of the structure. Delivery of roof material becomes challenging with mobile robots and may be done by a robot inside the structure. This robot may progressively deliver the material over the beam panels as each beam is placed on the roof. For the last few beams this robot could exit the structure and perform the delivery from outside. An alternative approach is to use the NIST RoboCrane system which may be installed on a conventional crane as shown in the lower part of Fig. 18. (The top part of Fig. 15 shows the RoboCrane moving a steel beam.) Besides the gripper for beams, the RoboCrane may carry a material tank and a special CC nozzle for roof material delivery.

5.2. Related information technology research

Fig. 16 represents the IT components in our future research directed at mobile robotics application in construction by CC. The diagram depicts a planning system, the output of which we plan to feed into a virtual system (simulation and animation), and eventually to a real system, once the required hardware becomes available. When connected to a hardware system, the proposed planning system will receive feedback at the implementation stage. Following is a brief explanation of each of the components shown in Fig. 19.

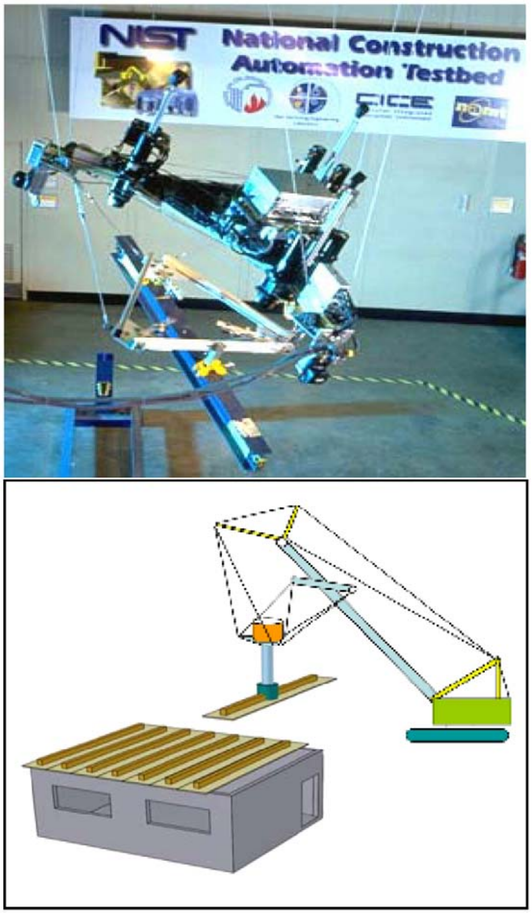

Fig. 18. RoboCrane for roof construction.

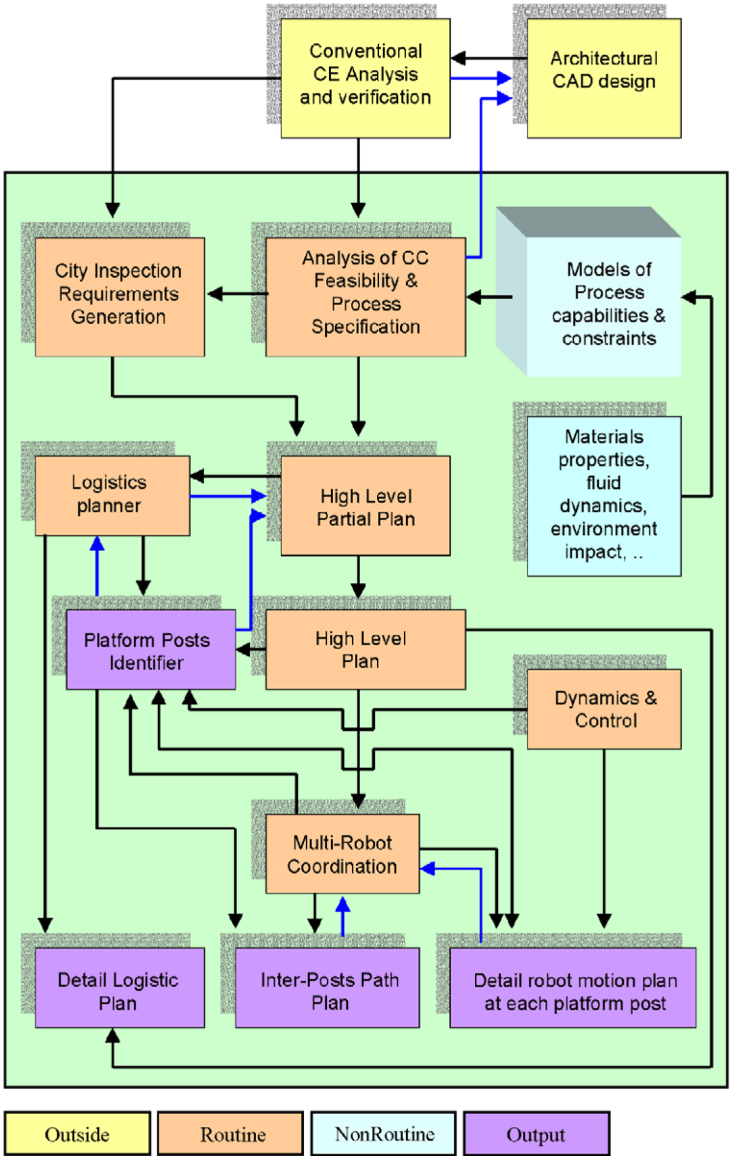

Fig. 19. IT components of future automated construction.

5.2.1. Analysis of CC feasibility

After possible refinements specific analysis is conducted for conformance to fabrication by the CC process. This activity is supported by various engineering models and simulation programs. For example, to verify the feasibility of constructing a certain section of a curved roof, fluid dynamics and material science models may be consulted to assure feasibility and specifications of feasible materials and process parameters. The design requirements and these process specifications are then passed to the planning system. Infeasible features are reported to the architect.

5.2.2. City inspection requirements generation

Design specifications are compared against local construction codes and an inspection plan is generated in accordance with the city inspection process, specifying various inspection types at various stages of construction. The inspection requirements are integrated with other construction requirements and are submitted to the planning system. Due to variations in local construction codes, the effort on this module will be minimal in the proposed research.

5.2.3. High level partial plan

This is a representation of possible meaningful sequences of high level activities (e.g., build living room, dispatch concrete truck, build roof of kitchen, etc.). A centralized planning system may generate the plan in whole, or generate it partially upon demand. The plan includes alternative sequences of activities which may be fetched if downstream high level planning runs into logistics conflicts or undesirable high level schedules.

5.2.4. High level plan

These are generated by a central planner the output of which includes items such as specification of platform posts (various stationary points at which robots anchor and perform their assigned operations) for various progressive stages of construction, without specific allocation of robots to posts. These high level plans, which specify what needs to be done at which post, are also sent to the multiple robot coordination module.

5.2.5. Multi-robot coordination

This module performs a decentralized allocation of tasks to the available robots based on various factors such as: extent of suitability of robot for the task (for example, a robot equipped with a plumbing assembly gripper is less suitable for electrical assembly as it must first change its gripper), closeness to the task post point, amount of concrete left in the robot tank, amount of batter charge left, etc. This module performs decentralized planning for maximum plan efficiency and agility. The module can change task allocation on the fly if unaccounted events (e.g., robot breakdown) take place.

5.2.6. Logistics planner

Details of the layout for resources (main concrete tanks, reinforcement, plumbing, and electrical modules, paint and charging station) and possible palletizing schemes, as well as dispatching and delivery schedules, are generated by this module, which operates in harmony with modules identifying the platform posts and schedule of operation at each post.

5.2.7. Dynamics and control

This module is in charge of actual delivery of tasks and assurance of successful performance. The module uses robot dynamics modeling and devises control schemes that incorporate objectives beyond mere task performance. These include: determination of the best position of the post with respect to the position of the feature to be fabricated or assembled to assume minimal power consumption, coordinated control of the robot and material delivery system for fabrication, range limits where deceleration and acceleration are needed, and the like.

6. Extraterrestrial applications

The ability to construct supportless structures is an ideal feature for building structures using in-situ materials. Hence, we plan to explore the applicability of the CC technology for building habitats on the Moon and Mars. In the recent years, there has been growing interest in the idea of using these planets as platforms for solar power generation, science, industrialization, exploration of our Solar System and beyond, and for human colonization. In particular, the moon has been suggested as the ideal location for solar power generation (and subsequent microwave transmission to earth via satellite relay stations). A conference on Space Solar Power sponsored by NASA and NSF (and organized by USC faculty) included several papers on this topic (http://robotics.edu/workshops/ssp2000).

Once solar power is available, it should be possible to adapt the current contour crafting technology to the lunar and other environments to use this power and in-situ resources to build various forms of infrastructures such as roads and buildings. The lunar regolith, for example, may be used as the construction material. Other researchers [12] have shown that lunar regolith can be sintered using microwave to produce construction materials such as bricks. We envision a contour crafting system that uses microwave power to turn the lunar regolith into lava paste and extrude it through its nozzle to create various structures. Alternatively, lunar regolith may be premixed with a small amount of polymer powder and moderately heated to melt the polymer and then the mix be extruded by the CC nozzle to build green state (uncured) depositions in the desired forms. Post sintering of the deposition may then be done using microwave power. Understanding of the following is crucial for successful planetary construction using contour crafting: (a) the fluid dynamics and heat transfer characteristics of the extrudate under partial-gravity levels, (b) processes such as curing of the material under lunar or Martian environmental conditions, (c) structural properties of the end product as a function of gravity level and (d) effects of extrudate material composition on the mechanical properties of the constructed structure.

One of the ultimate goals of the Human Exploration and Development of Space (HEDS) program of NASA is colonization, i.e., building habitats for long term occupancy by humans. The proposed approach has direct application to NASA's mission of exploration, with the ultimate goal of in-situ resource utilization for automated construction of habitats in non-terrestrial environments. We believe that the contour crafting technology is a very promising method for such construction.

7. Conclusion

Due to its speed and its ability to use in-situ materials, contour crafting has the potential for immediate application in low income housing and emergency shelter construction. Construction of luxury structures with exotic architectural designs involving complex curves and other geometries, which are expensive to build using manual approach, is another candidate application domain for CC. The environmental impact of CC is also noteworthy. According to various established statistics the construction industry accounts for a significant amount of various harmful emissions and construction activities generate an exorbitant amount of solid waste. Construction of a typical single-family home generates a waste stream of about 3–7 tons [13]. In terms of resource consumption, more than 40% of all raw materials used globally are consumed in the construction industry [14]. Construction machines built for contour crafting may be fully electric and hence emission free. Because of its accurate additive fabrication approach contour crafting could result in little or no material waste. The CC method will be capable of completing the construction of an entire house in a matter of few hours (e.g., less than 2 days for a 200 m^2 two-story building) instead of several months as commonly practiced. This speed of operation results in efficiency of construction logistics and management and hence favorably impacts the transportation system and environment.

There are numerous research tasks that need to be undertaken to bring the CC construction technology to commercial use. The activities reported in this article are the first few steps toward realization of actual full scale construction by contour crafting. Readers may obtain updated information on research progress and view video clips and animations of construction by CC at the author's website: http://www-rcf.usc.edu/~khoshnev.

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