Toward Total Automation of On-Site Construction - An Integrated Approach based on Contour Crafting

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ABSTRACT : Research at the University of Southern California addresses a new construction automation approach using a layered fabrication process called Contour Crafting (CC). The process aims at automated construction of whole structures as well as sub-components. 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. The basic Contour Crafting approach to construction, hereafter termed CCC (Construction by Contour Crafting), was presented in an earlier ISARC paper. This paper reports the new advancements in the CCC approach for integration of automated modules for tiling, for imbedding basic plumbing, electrical, and communication utility networks, and for automated painting.

KEYWORDS: automated reinforcement; automated tiling; automated painting; automated plumbing; automated electrical and communication network construction; Contour Crafting; mobile robotics

1. INTRODUCTION

Although automation has advanced in manufacturing, its growth in construction has been slow. With the exception of only a few successful attempts (see for example Balaguer *et al*, 2002) construction of whole structures remains largely as a manual practice. Conventional methods of manufacturing automation do not lend themselves to construction of large structures with internal features such as reinforcements, utility conduits, plumbing, electrical and communication line networks. This may explain the slow rate of growth in construction automation. A promising new automation approach is layered fabrication, generally known as solid free form fabrication or rapid prototyping, which uses an additive method and is capable of creating complex internal features. However, 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 (Khoshnevis, 1998). In CC fabrication of layers with thickness of several centimeters is made possible by means of planar trowels which are positioned at the mouth of the material delivery nozzle the position and orientation of which is controlled by computer. An animation of the process may be viewed at the author's web site (www-rcf.usc.edu/~khoshnev).

2. THE INTEGRATED CONSTRUCTION APPROACH

The proposed integrated approach to automated construction of whole buildings is based on CCC and includes the following components:

2.1 Automated fabrication of structures

Fabrication is performed by a new CC nozzle assembly similar to the one shown in Figure 1. This nozzle, which is being developed under our current NSF project, will be capable of co-extruding two different materials. The two side nozzles, each equipped with its own trowel, can deliver the materials that constitute the outside layer of walls, while the middle nozzle delivers the filler material which can provide structural strength. For example, the materials for outside surfaces may be plaster and the filler material may be concrete. The tubes shown have an inner coaxial tube thereby allowing for co delivery of two materials. The outside material may be delivered first to provide a rim that contains the filler material layer. To assure curing of the rims, the filler material deposition may be one layer behind the rim material deposition. Various approaches such as thermal and chemical techniques may be used to speed up the curing process. The middle nozzle has slot to allow for imbedding of reinforcements, as explained in the next section. Using this nozzle design it is possible to create openings within walls as utility conduits. A close-up animation which shows the working of this nozzle is also provided at the author's web site.

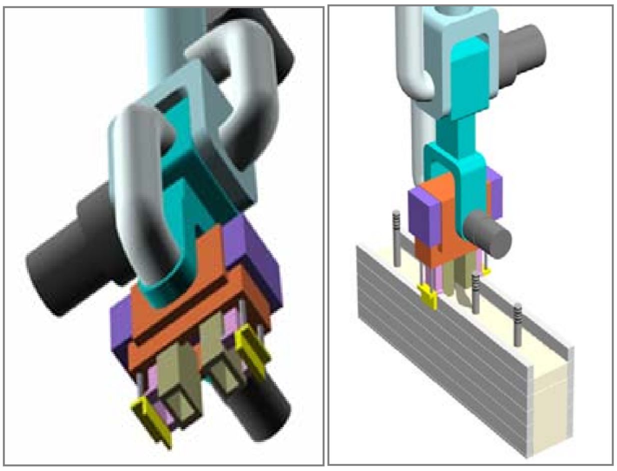

Figure 1. The nozzle assembly

2.2 Automated imbedding of steel reinforcement

Steel reinforcement may be built by creating two or three dimensional steel mesh within walls and columns using a progressive and layer-wise approach. Three steel elements and two robotic end-effectors will be needed as shown in Figure 2. For walls, a two dimensional mesh may be built by first imbedding the related vertical threaded elements at equal distances and interconnecting them with the horizontal "staple-like" element. The vertical elements are screwed or attached by snap fits with the layer below. The wall fabrication by CC then continues as shown in Figure 1 and the process is repeated for the next mesh layer, once adequate height is reached. The wall fabrication by CC then continues, and the process is repeated for the next

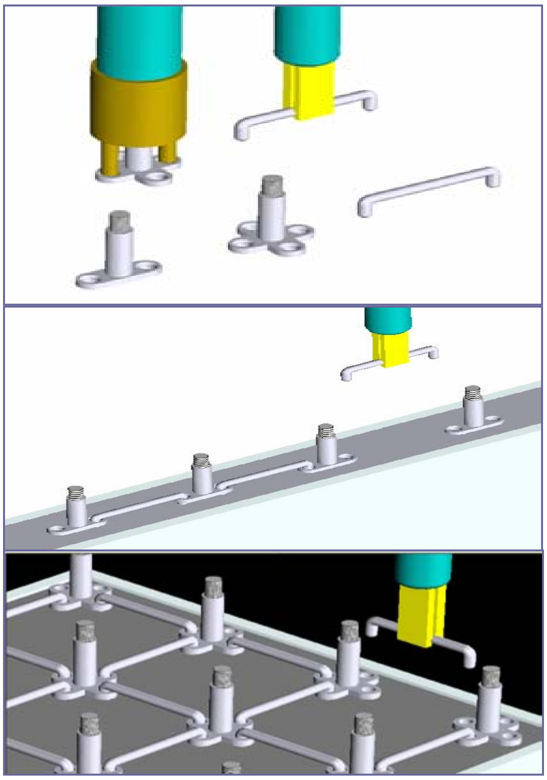

Figure 2. Reinforcement components and procedures for walls and columns

mesh layer. For columns, the associated vertical reinforcement elements are placed at equal distances on the lattice points of a two dimensional matrix.

2.3 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,

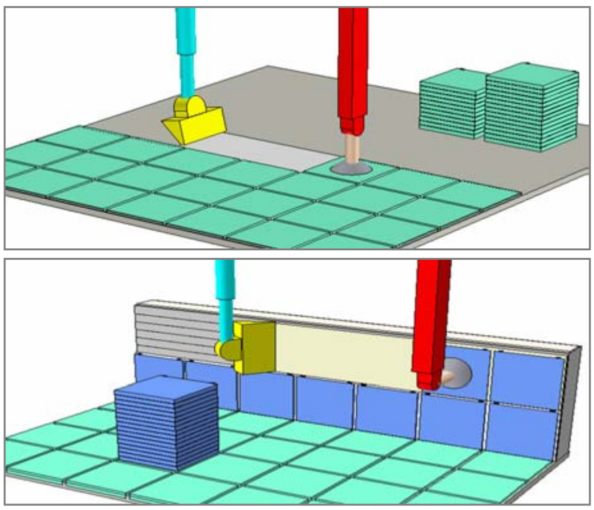

Figure 3. Automated Tiling

as shown in Figure 3. 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.

2.4 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 Figure 4, 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 Figure 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.

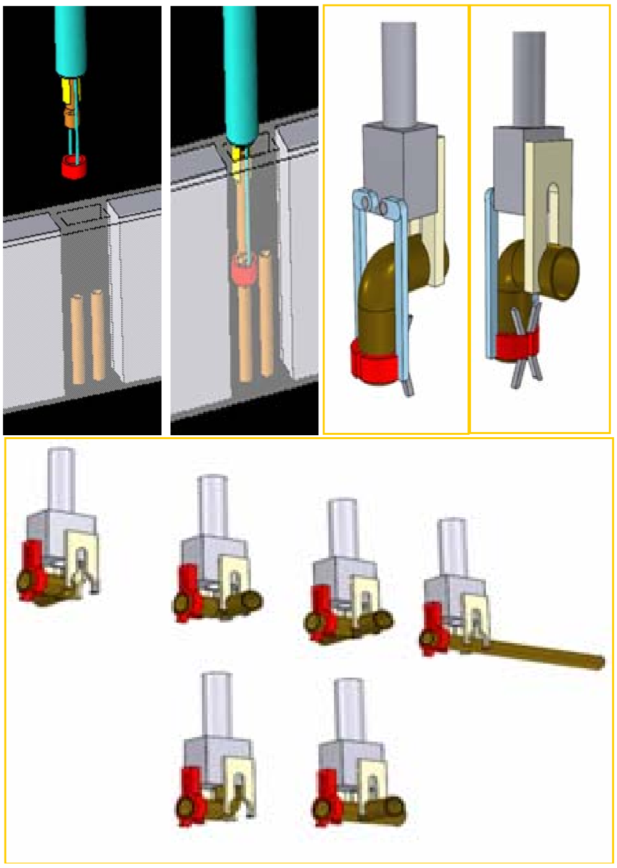

Figure 4. Plumbing modules & grippers

2.5 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 Figure 5, 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

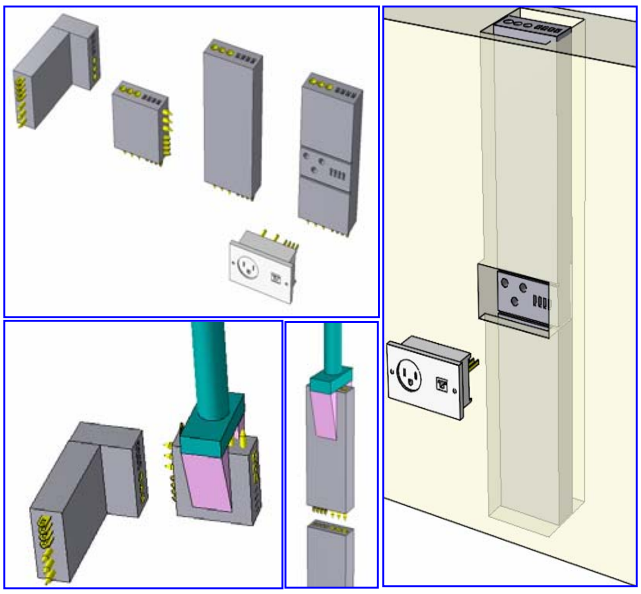

Figure 5. Electrical modules and assembly process

into the automatically constructed network.

2.6 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.

3.0 ROBOTICS APPROACHES

The original robotics approach proposed for Contour Crafting is depicted in Figure 6. This approach uses 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 alternative robotics approach for CCC is the use of an inverted Stuart Platform system, such as the one developed at the US National Institute of Standards and Technology and named RoboCrane (see Figure 9). Application of RoboCrane in CCC is currently under study by researchers at NIST. In this project a concrete delivery system is devised and used in conjunction with a CC nozzle installed on the RoboCrane platform. Ease of transport and installation are the major advantages of this approach.

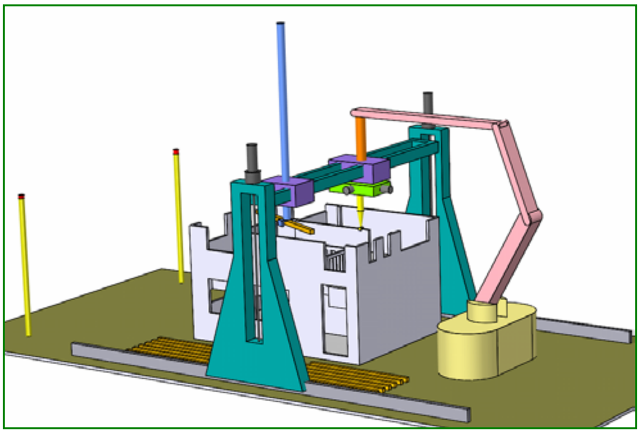

Figure6. CCC using a gantry robotics approach

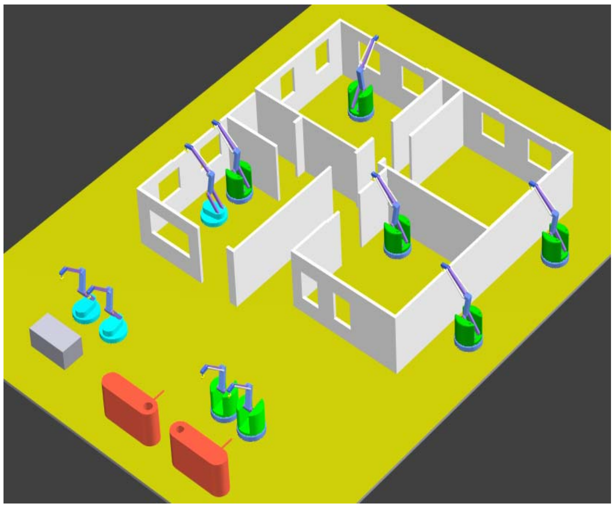

Figure 7. CCC using coordinated mobile robots for construction and other auxiliary activities.

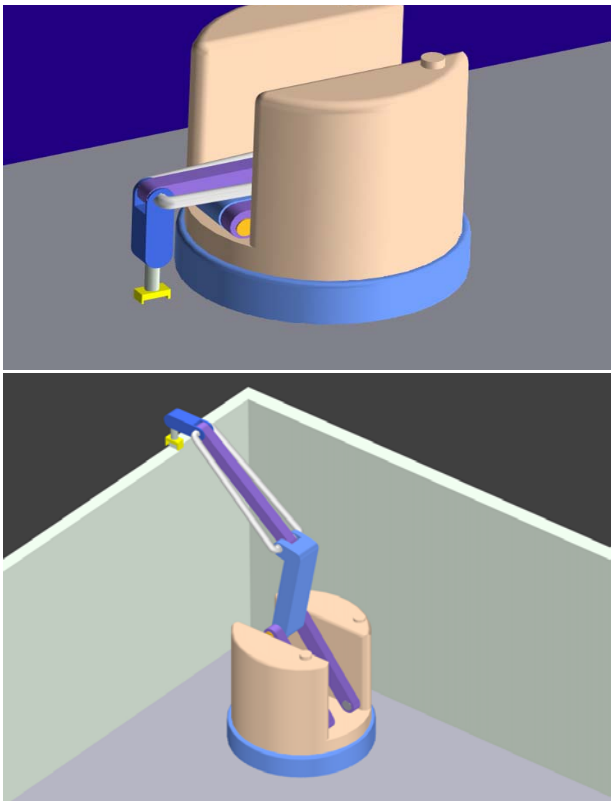

Figure 8. CCC using mobile robots

A third alternative robotics approach involves the coordinated action of multiple mobile robots. The mobile robotics approach depicted in Figure 7, 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, the possibility of scalable deployment (in number) of equipment, and the possibility of construction of structures with unlimited foot print. In this arrangement various mobile robots performing various activities such as fabrication, plumbing, electrical work, etc. work in coordination.

A CCC Mobile Robot may use a conventional joint structure, as shown in Figure 8, 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 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 all of the above robotics approaches. For planar roofs, beams may be used. Under each beam a thin panel may be attached to sustain the roof construction material delivered by the CC nozzle. In the mobile robotics approach 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 material delivery from outside. An alternative approach for beam positioning and roof material delivery, which may be used in conjunction with the mobile robotics approach, is the use of the NIST RoboCrane system. RoboCrane may be installed on a conventional crane as shown in the lower part of Figure 9 (the top part of this figure shows the RoboCrane moving an actual steel beam.)

4. CONCLUSION

The CCC approach can provide for rapid and automated construction of near-complete structures that would only need door and window and various fixture installations. Due to its speed and its ability to use in-situ materials, CCC 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 CCC. The environmental impact of CCC is also

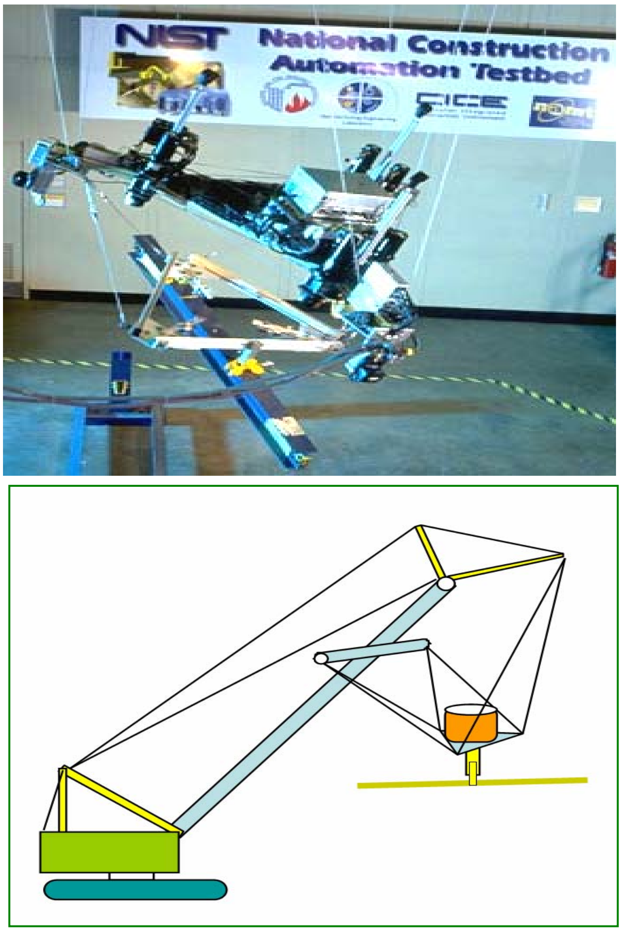

Figure 9. RoboCrane for roof construction

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 to 7 tons (City of Austin, 2002). In terms of resource consumption, more than 40% of all raw materials used globally are consumed in the construction industry (Lenssen and Roodman, 1995). Construction machines built for CCC 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. Estimates show that the CCC method will be capable of completing the construction of an entire house in a matter of few hours (e.g., less than two 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 at the author's web site.

5. ACKNOWLEDGEMENT

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