Automation in Construction 16 (2007) 224–231

AUTOMATION IN CONSTRUCTION

www.elsevier.com/locate/autcon

Freeform Construction: Mega-scale Rapid Manufacturing for construction

R.A. Buswell [a,*], R.C. Soar [a], A.G.F. Gibb [b], A. Thorpe [b]

[a] *Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, LE11 3TU, United Kingdom*
[b] *Civil and Building Engineering, Loughborough University, Leicestershire, LE11 3TU, United Kingdom*

Accepted 1 May 2006

Abstract

The utilisation of automation technology and processes control found in the automotive and aerospace industries is not paralleled in modern day construction. The industry also struggles to improve health and safety issues and still uses traditional methods of procurement. These problems are compounded by the diminishing skills in the labour force. Methods of production must change if these issues are to be resolved. Rapid Manufacturing is a family of digitally controlled additive processes that have the potential to impact on construction processes. This paper outlines some of the major issues facing construction technology and gives examples of the use of large scale Digital Fabrication in the industry. The term 'Freeform Construction' is defined. Potential applications derived from an industrial workshop are presented and results from a series of preliminary studies indicate the viability of mega-scale Rapid Manufacturing for construction.

Keywords: Construction Automation; Rapid Manufacturing; Freeform Construction; Rapid Prototyping; Solid Freeform Fabrication

1. Introduction

Rapid Prototyping processes such as Stereolithography have been utilised by the aerospace, automotive and consumer industries over the last two decades [1]. The utilisation of these methods within the construction industry is set to increase; architectural modelling is a growing application [2–5]. Processes such as 3D printing is becoming popular in mainstream architectural modelling applications; leading architects Foster and Partners (London, UK), for example, have a dedicated machine used by their Specialist Modelling Group.

Rapid Prototyping processes can be applied, conceptually at least, at any scale from desktop model to full scale building construction. Modelling is a typical application today, while full scale construction is more speculative. This paper reviews the status of the construction industry in terms of its problems and the use of Digital Fabrication. Rapid Prototyping and Rapid Manufacturing are described and construction applications are discussed. The paper responds to recent calls for the development of new processes [6] by defining the concept of Freeform Construction and discussing potential viability.

2. The problems facing construction

In terms of technological development and fulfillment of customer expectation, it can be argued that construction is decades behind other industries such as aerospace, automotive and ship building. The fundamental principles of construction have not changed for hundreds of years; the Romans invented concrete about 100 BC and 2200 years later we are still using it as a primary build material *and* (more or less) controlling placement with the human hand. Construction technologies are limiting imagination and hence stifling innovation; new methods of production and assembly often result in moving the 'hand trades' away from the construction site rather than developing radical new processes. Often the procurement and legal requirements that enable construction act as a disincentive to try different approaches.

Competition for projects concentrate on first-cost; the cheapest bid wins and there is little time, money or energy to invest in innovation. The industry is also conservative and innovations only generate incremental changes. Where changes

* Corresponding author. Tel.: +44 1509 227690; fax: +44 1509 227549.
E-mail address: r.a.buswell@lboro.ac.uk (R.A. Buswell).

0926-5805/$ - see front matter
doi:10.1016/j.autcon.2006.05.002

and improvements are made, the transient nature of the work and workforce often means that these improvements are not adopted on new projects as they might in a more 'static' manufacturing environment. There is a growing skills shortage, which will be compounded in the future by the aging population apparent in the UK and alike countries. Safety is still an important issue; construction remains a hazardous environment. In addition, the industry is likely to face increasing pressures from developing environmental issues [7].

The UK government has been addressing these issues through a succession of initiatives, prompted by the Latham and Egan reports [8,9] and ultimately by 'Constructing Excellence.' The drive is towards leaner, better Modern Methods of Construction [10]. Some of these issues have been addressed by standardisation and pre-assembly [11]. There is however, a need for a more radically different solutions. As human endeavour pushes further forward, construction will need to be able to respond to unique challenges in aggressive environments such as for polar, desert, chemical contamination and off-world applications. We will need to respond to environmental issues with new materials and new solutions for buildings at end of life.

Process automation offers a large departure from conventional methods of construction. This has largely been investigated in terms of robotics [12–16]. Creating large scale 'on-site factory' environments have been demonstrated by the construction of the Shimizu Corporation building [17] and others.

3. Rapid Manufacturing

Rapid Manufacturing, Rapid Prototyping, Solid Freeform Fabrication, Additive Manufacturing Technologies, all refer to the same family of processes. In broad terms, these processes all produce components by adding, or building up, material to form an object. These processes contrast traditional methods that are either: *Subtractive*, starting with a block and machining away the material that is not required; or *formative*, shaping or casting material in a mould.

These methods were developed originally to quickly produce prototype models. The name Rapid Prototyping described the time saving associated with the negation of the human modeller, or tool maker employed to create the object for evaluation as part of the design process. Rapid Manufacturing is the term applied when Rapid Prototyping machines are used to produce *end use* parts directly. In the US, *Solid Freeform Fabrication* is the preferred term for Rapid Prototyping or Rapid Manufacturing. The term Rapid Manufacturing will be used throughout this paper and some common processes are summarised in Table 1.

Table 1
Summary of common Rapid Manufacturing techniques [1]

Process	Description
Stereolithography (SLA)	Liquid photopolymer resin is held in a tank. A flat bed is immersed to a depth equivalent to one layer. Lasers are used to activate the resin and cause it to solidify. The bed is lowered and the next layer is built and so on.
Fused Deposition Modelling (FDM)	Extrudes a narrow bead of hot plastic and is selectively deposited where it fuses to the existing structure and hardens as it cools.
Selective Laser Sintering (SLS)	Utilises a laser to partially melt successive layers of powder. One layer of powder is deposited over the bed area and the laser targets the areas that are required to be solid in the final component.
3D Printing (3DP)	Based on inkjet printer technology. The inkjet selectively deposits a liquid binder onto a bed of powder. The binder effectively 'glues' the powder together.

All of these processes work on similar principles, Fig. 1 depicts the 3D printing process. A 3D solid model of the desired component is created in CAD[1] software (1). The model is then typically translated into 'STL'[2], a standard data format that can be used by most Rapid Manufacturing machines. This describes the surface of the object and can then be 'sliced' into layers so that the part can be constructed sequentially (2). Each layer is then sent to the machine (3) and the information used to control the location of a printer head. The printer head deposits a binder on a fine layer of powdered material where the layer is to be made solid[3] (4). The machine reconstructs a 3D object by sequentially bonding these '2D' layers of material.

Rapid Manufacturing has come through an evolution. Early versions could not produce robust components that could be classed as 'end-use' parts and this was largely down to the quality of the materials. Materials development plays a key role in realising true functionality in parts produced using Rapid Manufacturing technologies. Highly engineered components, such as camshafts, gearboxes, etc., can not be manufactured yet using SLA or SLS type processes. Within the additive process family, however, advances in technologies such as Rolls Royce's (Derby, UK) Shaped Metal Deposition process and Optomec's (Albuquerque, USA) Laser Engineered Net Shape process are capable of providing fully dense metal parts with fewer defects than the forging or casting alternatives [18,19].

It should also be noted that, contrary to the name, Rapid Manufacturing is not concerned with speeding up manufacturing process; it simply eliminates the need for tooling and so shortens time *to* manufacture. A useful by-product of this approach is almost unlimited geometrical freedom and that moving parts can be constructed in a single build, negating the need for assembly. The perceived benefit of these processes is therefore *adding value* to products. A principle driver for Rapid Manufacturing is product customisation and/or personalisation at no extra cost. There is significant interest in these technologies for the delivery of medical services such as better fitting burn masks that improve recovery and the investigation of hydrogel scaffolds for tissue repair applications [1,20]. Rapid Manufacturing has found a niche market in dental care. In the US, Invisalign Technologies [21] offer a clear plastic product

[1] Computer Aided Design or Drafting.
[2] Standard triangulation, or Stereolithography Language.

[3] In actual fact, the Z Corporation 3D printing process (depicted in Fig. 1) actually deposits an activating agent. The second half of the two part binder is premixed with the powdered material.