Printed buildings: an international race for the ultimate in automation

3D printing is already here. The market for common household objects is small, but is predicted to be worth US$3 billion by 2016. But what about buildings? Here **David Smith** catches up with three world leaders in large-structure print technology to chart the progress and the possibilities

Scientists working in three separate countries each believe they have developed 3D building printing technologies which could transform the global construction industry.

The three men, who claim to have advanced their individual strategies independently of each other, have each found a way to use 3D printing technology on such a large scale that entire buildings could be printed out of machines. Although there are family resemblances between their methods, there are also significant divergences.

Two of the scientists are blessed with university positions and government funding. The academic who has been working on his method for the longest time is Behrokh Khoshnevis, a Professor of Engineering at the University of Southern California. His Contour Crafting process has produced 24 patents worth around US$1 million.

Meanwhile, in England, Dr Richard Buswell is leading a project by Loughborough University's Additive Manufacturing Research Group to develop 3D Concrete Printing technology which uses cement-based mortars to create large structures.

Finally, there is the Italian inventor, robotics expert Enrico Dini, who is based in Tuscany. Dini founded the Monolite UK company and hopes to produce and sell 3D printers under the name D-Shape. In some ways, he is the odd man out because he is a lone wolf, operating independently of academic institutions. Without a salaried position to fall back on, his journey has been the most traumatic.

> ***"My life was a bloody hell. It cost me my savings, sent me into mountains of debt and destroyed my marriage"***

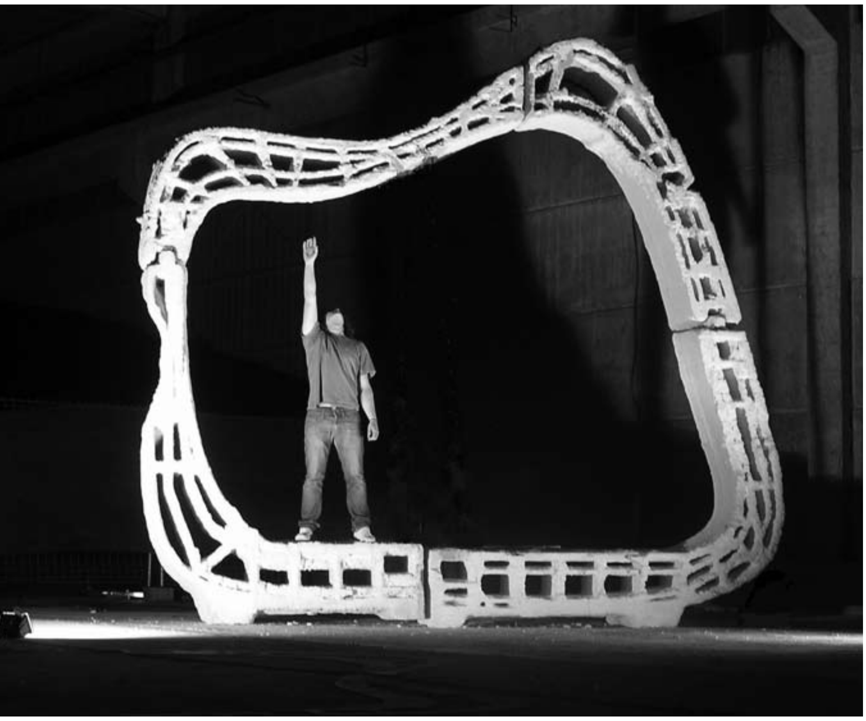
Dini quit a full-time job in 2006 to devote his life to 3D printing, but his obsession ended up costing him his marriage and plunging him into crippling levels of debt. He has described it as a "journey to hell", but he remains optimistic that one day his invention will change the world.

Loughborough University's Additive Manufacturing Research Group is focussing on double-curved panels for large buildings at the higher end of the market. Photograph by Agnese Sanvito

Another key distinction to make is that the Loughborough team is targeting the high end of the architectural market, whereas both Dini and Khoshnevis dream of making cheap housing in the third world.

Dr Buswell said: "We are focusing on producing double-curved panels for large buildings. It's not aimed at cheap and fast construction, but at the higher end of the market. In the end, your approach depends on where you think the quick wins are. In principal, you could use our machine to print the walls of a building by programming it differently, but in reality you have to adapt the process to do specific applications because of the scale.

"We see Concrete Printing as one



Rather than concrete, Enrico Dini's printers use an inorganic binding ink and ordinary sand, and no water is needed. As the two components meet outside the nozzle the machine does not clog up

design method in an architect's arsenal. For simple building processes, conventional methods could work out cheaper. Our techniques would be ideal for companies we are collaborating with, such as Foster + Partners and Buro Happold. They make funky but expensive buildings. Later, once the innovative technology is working at the high end, these features will become cheaper and move into the mainstream."

Khoshnevis has a more epic vision of what can be achieved. "Contour Crafting would be of most benefit to developing countries to eradicate their slums and raise standards of living in the world," he said. "But it can also be used to construct emergency-shelters to house millions who are uprooted by wars and natural disasters."

Dini shares Khoshnevis's belief in his technology's world-changing potential. "It could be used to build cheap houses in developing countries, but only once the printer is simplified to be managed like a tool rather than a machine," he said. "It's a tricky matter and needs more investment but this vision is what keeps me going. I've made huge personal sacrifices and I will never make a lot of money, but my reward will be making the world a better place."

The three men have discussed their projects, but have never collaborated. There is, though, a keen awareness of each other's work and a sense of rivalry.

Despite their differences, they have a great deal in common. All three believe passionately that 3D printing will eventually make a radical contribution to construction. But they acknowledge, too, that the technology is so 'disruptive' that this conservative industry will be slow to embrace it.

Khoshnevis said: "The construction industry is based on short-term planning. Companies won't invest in technology that takes years to mature. In the drug industry it takes years before new products are considered safe for the market. Construction companies know there will be expenses involved in doing tests to attain building codes. So they'd rather let someone else pay for the early-stage research and development, then use it."

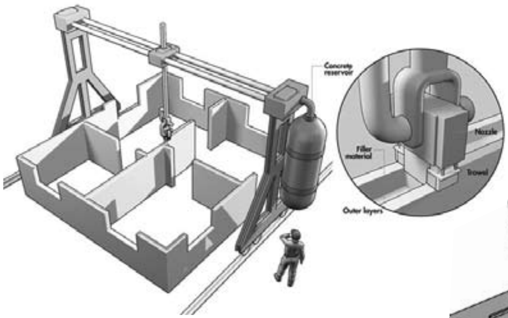
A further obstacle for all disruptive technologies, Khoshnevis says, is that the infrastructure is not yet in place to support them. "What's the point in having a technology which can build a house in a day when the US building inspectors come out 10-12 times to check things over and it takes weeks to schedule all the appointments?"

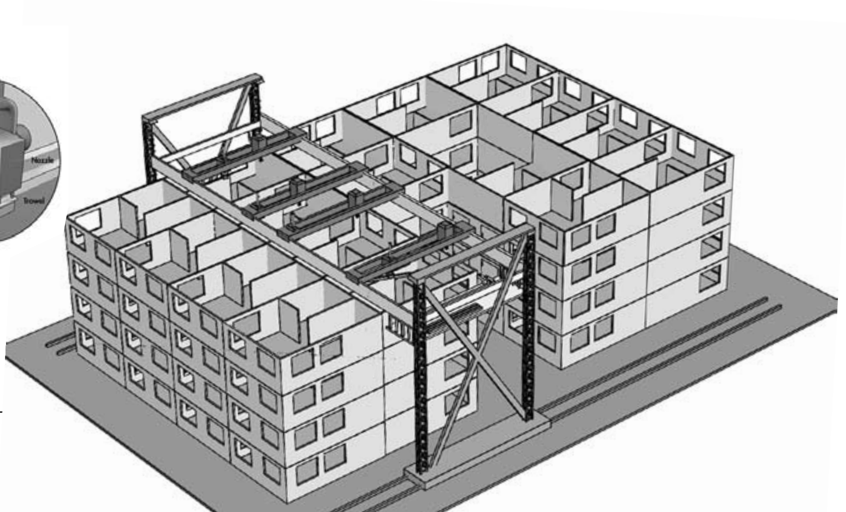
Khoshnevis consoles himself with the knowledge that it took the 19th century Scottish inventor Alexander Graham Bell 15 years to commercialise his telephone in the US. "They only had the telegraph, but the President of Western Union famously said: 'When people have the telegraph why would they want to use the telephone?' And he was right because the infrastructure was not there.

"People didn't have telephone lines so you had to make calls at the telegraph station. This was expensive and inconvenient. It was better to use the line for many quick telegraphs than a couple of guys saying 'hi, how are you?' The telephone didn't make business sense until the infrastructure was ready."

Dr Buswell agrees that the industry's caution is a problem, but he puts it a different way. "We have to bear in mind that things falling off buildings and killing people is not an option and safe environments are paramount, so there's a natural and sensible conservatism towards new technology. It will take a lot of high-quality engineering to refine the process so the industry has confidence."

Computer generated image of structure-printing on the moon. In 2011 NASA awarded USC's Khoshnevis a grant to develop lunar applications





Drawings from USC's Center for Rapid Automated Fabrication Technologies shows how, in theory, a print-head rigged to a gantry could print full-size buildings

One final congruity is the belief that their technologies could combat global warming. "With 3D printing there's no material waste. It's a fully electric process, which is clean and quiet," said Khoshnevi. "But the main saving is people don't have to drive back and forth to construction sites, which saves a massive amount of fuel."

It works small, so...

The original inspiration for the technologies is the "rapid prototyping" process which has been around since the early 1980s. This is a quick way of printing out small, one-off items from fused plastic, or metal powder, using computer-controlled lasers in printers. The process is now often called additive manufacturing, to distinguish it from old-fashioned subtractive manufacturing, which created components by shaving bits away.

Many architectural firms use prototyping labs to print out models of their building designs. The process takes a day, compared to two weeks for a craftsman. Once the digital file has been created, multiple models can be created at little expense.

Commercial DIY printing kits have become so commonplace and are routinely given away as Christmas presents. Brooklyn-based MakerBot has sold thousands of its 3D printers at around US$1,000 apiece. The growth in the market is such that the 3D printing industry is predicted to be worth US$3 billion by 2016.

The printers are linked up to CAD software on a computer. The owner can sketch out a 3D model and instruct the printer to fabricate the desired object. The number of applications is almost infinite, but the they are often used to fashion household objects such as bottle openers, doorknobs, or clothes pegs.

"Our processes are similar to these smaller printers, but the real challenge for the Loughborough team - as well as for Dini and Khoshnevis - is in scaling up," said Dr Boswell. "There's a big difference between creating something the size of a telephone and the wall of a building. There are both material and physical constraints at larger scales."

Khoshnevis was the first to envisage using 3D techniques in the construction industry. Originally, he had created his technology to construct moulds for industrial parts. But he began to think about building a 3D machine which could help to rebuild infrastructure following natural disasters after Los Angeles was struck by an earthquake in 1994. The challenge was dear to his heart as earthquakes plague his native Iran.

Khoshnevis's computer-controlled crane, or gantry, operates on the same principles as commercial 3D printers. A robot squirts out thick liquid concrete through a nozzle at high pressure. The layers build rapidly, with the lower ones hardening enough to support the increasing weight.

Trowels smooth the outer walls, while voids are created inside the walls by programming the nozzle to leave blank areas. The robotic arms place pipes inside voids and weld sections together.

Khoshnevis claims Contour Crafting can build a square foot of wall in less than 20 seconds, a whole room in an hour and a 200m2 single-story house in a day.

> ***"In the end, your approach depends on where you think the quick wins are"***

The full-scale machine splits into three pieces in order to fit onto a small flat-bed truck. All construction happens on-site, where humans play a supporting role. They lay out supplies for the robotic arm and prepare fresh batches of concrete. They install windows and doors as the task is not worth automating, says Khoshnevis.

The machine works directly from CAD drawings, which allows architects much greater freedom of expression than conventional building methods. The robots can build almost anything from a drawing.

"Primarily, Contour Crafting can do four things better than traditional methods," he said. "The first is to build structures with complex geometry, which fascinates architects. There are practically no limitations to the complexity of curvatures.

"The second application is to build remotely in dangerous, or inhospitable environments. It could build a protection wall against a damaged nuclear power plant, for example. The third use is to construct small structures in spaces which can't easily accommodate people.

"Finally, Contour Crafting allows construction using very hot materials, or ones that release dangerous gases. This might be necessary if some high-performance materials have been created using chemical processes."

Printing in space

Khoshnevis is developing several uses for his technology, including creating large commercial structures. But the most inspiring commission came last November when NASA awarded him a grant to build lunar structures as part of their NASA Innovative Advanced Concepts (NIAC).

"It's a challenging project which will take years to be implemented, but we've done some demos with lunar soil and shown the feasibility of the concept," Khoshnevis said.

His team's next step is to test the process at the Desert Research and Technology Studies (D-RATS) facility in Arizona. "In a few years we will do a full-scale demo there and after that, we would look seriously at the logistics of launching a robotic system into space," he said.

No less visionary is his more earthly aspiration to eradicate the world's slums. Khoshnevis says this will be possible because automation cuts costs dramatically.

"It's the same principle as for hand-made shoes, or tailor-made suits. They are far more expensive to make. Automation brings construction costs down to 25% of manual approaches because labour costs are 50% of the total cost and they can be slashed almost to zero," he said.

Khoshnevis admits that construction jobs would be lost, but argues that the benefits outweigh the downsides. "Construction jobs are the most dangerous of all, worse than mining or agriculture. Every year thousands are killed, paralysed and

The print nozzle developed by USC's Center for Rapid Automated Fabrication Technologies

Detail of structure printed by Loughborough's Additive Manufacturing Research Group. Photograph by Agnese Sanvito

maimed. You don't see many old, or even middle-aged people because it destroys the body," he said. "Contour Crafting would open the industry up to women and the elderly. People could focus on creativity rather than doing debilitating, repetitive tasks."

Like Khoshnevis, the Loughborough team's 3D Concrete Printing (3DCP) process was inspired by additive manufacturing. Engineering colleagues discussed the possibility of using 3D methods for construction projects and put a funding proposal together. It won an internal competition to develop flagship research projects and the Additive Manufacturing Research Group was awarded £1.2 million five years ago to develop the technology.

"Our real challenge was to take the additive techniques and scale them up massively," Dr Buswell said. "Instead of doing something the size of a telephone, we're working on building the wall of a building. That means there are both material and physical constraints which need to be resolved."

The Loughborough team built a 3D rig out of motors and chains inside a big square box measuring 5m by 6.6m. The nozzle can be positioned anywhere to obey the digital programme's instructions.

Focusing narrowly on double-curvatures brought swift results. In 2010, the team manufactured the 'Wonder Bench', which was the world's first reinforced concrete components with double curves. Its printed material was about 95% the strength of a conventionally cast bench. Then, in 2011, they developed the world's first double-curved panels with conformal voids which were printed without casting.

"Generating double-curvature twist is expensive. Single curves are quite achievable, but doubles become quite challenging which is why we've focused specifically on ones to clad buildings," said Dr Buswell. "It frees up architects who want to design complex curved buildings in the same way as engineers design complex curves for cars."

The current three-axis gantry has its limitations, however, and the team has commissioned a seven-axis robotic arm in order to maximise printing quality, speed and capacity.

Unlike the Contour Crafting machine, which is designed to build houses in situ, the Loughborough machine will be factory-based.

"It would be based in a factory with a whole load of robotic arms configured to do various jobs. The finished components would be taken to building sites on lorries," he said. "It would also be possible to set up temporary factories. The robotic arms could be shipped in on lorries and then, it's a question of bringing in the requisite materials at one end and taking out the panels at the other."

Waiting for a breakthrough

The controlled environment at Loughborough is in stark contrast to the emotional journey of Enrico Dini which began in 2004 when he started to work on his 3D printing technology with a couple of colleagues in a garage in Tuscany. For the first 18 months, his life descended into chaos as he juggled commitments all over Italy: His family and child were in Rome, his 3D research was in the centre of Italy and his full-time job as an expert in footwear robotics was in the north.

After much to-ing and fro-ing between his three bases, he decided the situation was untenable and he quit his job. "The 'terrible date' was November 2006, when I decided to make 3D printing my life's work," he said.

Following a fall-out with his colleagues in Italy, Dini set up a company in London called Monolite UK. He moved to Notting Hill in an endeavour to persuade equity funds to invest in his technology. Meanwhile, he raised money by re-mortgaging his apartment for €75,000, borrowing €50,000 from his father, and using up €15,000 in savings.

Professor Berok Khoshnevis, Director of the Center for Rapid Automated Fabrication Technologies, University of Southern California

The Tuscan regional Government refused to back his project, but the Italian Chamber of Commerce put in €400,000 and borrowed a further €600,000 from the bank.

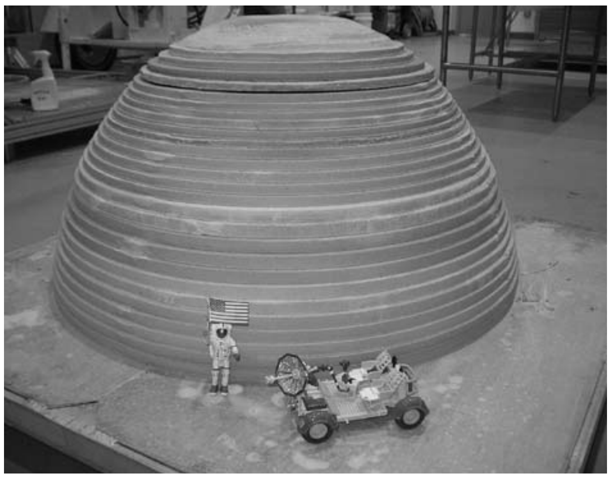
It was an enormous gamble and it didn't work out financially. While he was in London, the company lost €1 million in eight months, the same amount he had spent in the previous four years. Dini decided to retreat back to Italy.

"My life was a bloody hell. It cost me my savings, sent me into mountains of debt and destroyed my marriage," he said.

As befits a man of Dini's independence of spirit, his 3D method differs from the other two by not requiring cement. D-Shape's printers use a special inorganic binding ink and ordinary sand as the only raw materials. No water is needed. As the two components meet outside the nozzle, the machine does not clog up and can maintain its accuracy of 25 DPI.

Dini claims the finished product is a hard, marble-like material which can be used for anything from park benches to two-storey buildings.

"My dream is to make housing in developing countries, but a lot more research is needed," he said. "But the machine can already be used to make a lot of different objects. It could produce



Models of printed lunar buildings produced for NASA by USC

Sculpture by Bathsheba Grossman printed with D-Shape

warehouses which look more like Cathedrals where every 20m beam has been shaped in whatever way you wish."

For now, reality intrudes on his aspirations. Dini's life is a whirl of trying desperately to strike business deals to get more money to invest more money in developing projects, whilst dealing with the company's day-to-day business at its Tuscan factory, where he employs four workers.

> ***"I've made huge personal sacrifices and I will never make a lot of money, but my reward will be making the world a better place"***

"My first thought is always that I need to get an egg to eat today rather than worry about a chicken tomorrow," he said. "We do have quite a few purchase orders: We're selling printed sculptures at around €12,000 each and I'm sending printed lamps out to a Canadian client.

"We're also creating artificial coral reefs for coral restoration in the south of Italy - we can print 3D reefs with lot of cavities inside to provide refuge for fish. And we're manufacturing cladding to put around concrete columns to make them more attractive for hotels."

For all the different applications of his technology, Dini has yet to make a major commercial breakthrough. "Our income from sales is ridiculously low, around €10-15,000 per month. But this could easily be a multi-billion dollar business if we got the right investment," he said.

Dini is obsessed with finding investors, and with good reason, as they would allow him to pay off his debts. He says an Israeli-Swiss fund is close to investing €15 million in Monolite. If that doesn't work out, he has a presentation to make in London to one of the biggest engineering firms in the world, as well as a meeting at the end of June with Dutch architects who are interested in developing housing in third-world countries.

He also has plans to create a worldwide network of D-Shape companies which operate independently, but share their technological advances.

"I can talk for 40 minutes about potential projects, but I need investors who are not looking to the short- or medium-term. I need to do seven or eight years more research and it's hard to say exactly how much money I need, or how I will spend it.

"If someone had given me €50 million seven years ago I would already have reached the point where we go into orbit. But for the moment, it's a question of waiting and remaining calm like a snooker player," he said.

Of course, as established academics, Dr Buswell and Professor Khoshnevis do not have to face Dini's financial anxieties. But that does not mean they do not crave more money for research. Dr Buswell's funding runs out this year and he has to apply for more grants to continue developments.

"We are at the prototype stage. We have proved the technology in the lab but we're some way off commercialisation," he said. "We need to do follow-up projects, in conjunction with our industrial partners to explore how to move to a more industrialised project.

"How fast we go depends on funding. If someone said money was no object I'd say we could construct a building in two years. We've received substantial interest from major architectural firms, but it's still early days."

Khoshnevis has enjoyed roughly US$3 million of investment for a variety of applications. There are accords between projects and even the NASA research will help him learn about terrestrial applications. But the reality is that each application needs its own funding.

"It would take millions more dollars to perfect the techniques," he said. "But when we get the funding and the right infrastructure is in place, 3D printing will make a massive difference to building methods, costs and the look of our urban environment. I'm confident that it will raise standards of living throughout the world."