3D printing – the breakthrough technology that could change the world

Long the stuff of science fiction, 3D printing is not only real, but finding new applications – from aerospace to biomedicine – every day. A careful analysis of the patents behind the technology suggests that home 3D printers could become as ubiquitous as PCs within the next few decades

By **Darshan Mujumdar**

Additive manufacturing or three-dimensional (3D) printing is the process of making three-dimensional solid objects from a digital model. Unlike conventional manufacturing, which uses subtractive methods, 3D printing uses additive processes whereby an object is created by adding material in layers. Such techniques require less material than subtractive manufacturing, where material is wasted in the removal process. Since the start of the 21st century there has been a spurt in the sale of 3D printing machines and prices have already dropped dramatically.

This ground-breaking technology has applications in a variety of fields, including jewellery, footwear, architecture, engineering and construction, automotive, aerospace, dental and medical, education, and geographic information systems.

Bio 3D printing – a new concept that could solve a multitude of issues in medicine – can be used to make living organs from a patient's own cells in 3D printed casts. For instance, the Cortex orthopaedic cast is a custom-fit, breathable, lightweight, recyclable and washable exoskeleton that allows safe recovery from fractures. The cast mimics the body's trabecular – the small honeycomb-like structure that makes up the inner bone structure – and allows air to circulate during the healing period. The Cortex cast employs a fitting system similar to other casts, along with the use of X-rays to determine bone fractures. Interestingly, this prototype, which was developed by Jack Evill, used a hacked Xbox Kinect for 3D scanning. However, work has already started on a more sophisticated and precise scanning process.

In early 2013 Nokia became the first major phone company to embrace 3D printing technology when it released a 3D printing kit to customers, allowing them to design their own cases for the Nokia Lumia 820.

As is apparent, 3D printing could bring a host of new possibilities to our lives and is definitely something to look forward to in the near future. This article studies the evolution of this industry over the last decade, analyses patenting trends around the globe and takes a look at companies at the forefront of 3D printing.

Industry growth

Supporters say that 3D printing technology marks the democratisation of manufacturing and will introduce a new age of mass personalisation and innovation. 3D printers, also known as 'desktop factories', make more efficient use of resources and could transform production processes in the future. For these reasons this technology, with its broad applications, is being aggressively pursued by academia and business alike.

The 3D printing and additive manufacturing industry was valued at US$2 billion as of 2012. Experts believe that it will play a major role in the future of the US$22 billion global power

tools industry. Currently, there has been extensive use of the technology in medicine, with the production of custom-fit prosthetics and hearing aids, and also in the automotive industry, where it is being used to produce spares, potentially eliminating the need to stock spare parts. With industrial manufacturing growth rates of more than 100% for 2011-2012, 3D printing is expected to continue to grow at a healthy rate.

Revenues from the sale of 3D printers in 2012 amounted to nearly US$200 million, while for 'personal' 3D printers this value was estimated at US$38.2 million. Sales of personal 3D printers experienced a significant decline in 2012, with growth of just 46.3%, as compared to 346% on average annually from 2008 to 2011. Although consumer-oriented 3D printers grab media attention, they represented less than 2% of the US$2.2 billion 3D printing industry in 2012 (see Chart 1).

The price of 3D printing computers is one of the major roadblocks to large-scale adoption. The average industrial 3D printer currently sells for about US$75,000, while some highly sophisticated machines cost upwards of US$1 million. With respect to personal versions, fused deposition modelling printers — which were previously priced at US$30,000 — are now more affordable at around US$1,000. The issue of price pertains to raw materials too. As the technology creeps its way closer towards mainstream manufacturing, volumes will increase, causing prices to fall. Moreover, new materials are regularly being tested for 3D printing, which will further reduce operating costs.

The recent M&A activity by top companies within the industry also shows renewed interest in 3D printing. 3D Systems, a South Carolina-based company worth US$4.38 billion by market capitalisation, acquired Z Corporation and Vidar Systems in 2012. In 2013 it acquired Huntsman's stereo-lithography product line — Geomagic and Coweb — and recently the company also bought an 80% stake in Phenix systems, a French provider of direct metal selective laser sintering.

Stratasys Ltd, a US$4 billion company by market capitalisation, was formed in December 2012 by the merger of 3D printing giants Stratasys Ltd and Objet Ltd. In 2013 Stratasys Ltd purchased MakerBot in a stock deal worth US$403 million, adding desktop 3D printing capabilities to its already strong industrial printing portfolio.

Boeing has been using Stratasys' 3D printers to make components, producing more than 20,000 printed parts including an entire cabin for an aircraft. The 787 Dreamliner has about 30 printed parts installed in its structure. One of the reasons for using additive manufacturing in this industry is that it can facilitate the construction of lighter, better-designed aircraft, which helps to improve fuel efficiency.

Even NASA has ventured into 3D printing and successfully tested a 3D printed rocket engine injector. A quote from Michael Gazarik, NASA's associate administrator for space technology, highlights how important the technology is to the organisation: "NASA recognizes that on Earth and potentially in space, additive manufacturing can be game-changing for new mission opportunities, significantly reducing production time and cost by 'printing' tools, engine parts or even entire spacecraft."

But there has also been scepticism towards 3D printing. In June 2013 Terry

Chart 1. **Recorded and projected market values of 3D printing**

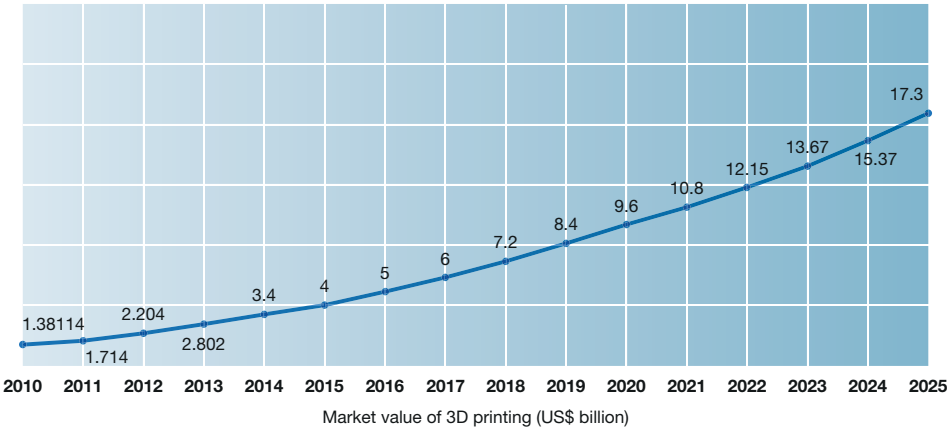
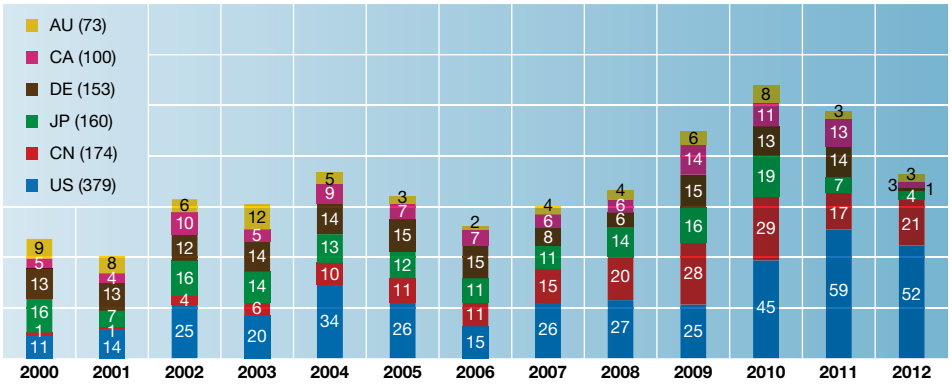


Chart 2. **Patent filing trends: top six countries**



3D printed gun – Liberator
The world's first 3D printed gun. In May 2013, high-tech gunsmithing group Defense Distributed test-fired the first 3D printed gun. There has been much scepticism about 3D printing of guns since then, revolving around the legal and practical implications

Source: Forbes – *www.forbes.com/sites/oliverherzfeld/2013/05/29/protecting-3d-printingdesigns-and-objects/*

Gou, chairman and president of Foxconn, one of the world's largest electronics manufacturing companies, severely criticised and pointed out many drawbacks of the technology, especially when it comes to mass production. This is partially the reason why 3D printing services are the current focus. While personal 3D printers are still being perfected, 3D printing service providers such as Shapeways, Sclupteo and Materialise provide design and printing options for consumers. Such companies have highly sophisticated machines and act as third-party manufacturers to creative people all over the world, providing uniquely designed objects to consumers.

Patent filing trends

Chart 2 depicts the patent filing trends in the top six filing countries in the 3D printing technology space. An analysis of the patents reveals that the United States is the undisputed leader in this field, with an average annual growth rate (AAGR) of 25% from 2000 to 2011, followed by China, with an AAGR of more than 45% during the same period. Canada has significantly increased its patenting activity in 3D printing, with AAGR close to 23% in filings.

As home to some of the biggest firms in the industry, the United States is the most important market for 3D printing technology. 3D Systems Corporation and Stratasys Ltd not only hold valuable patent portfolios, but are also keen to continue developing their technology. China has increased its patent filing activity in this domain as well, with about two-thirds of Chinese patents having been filed in last five years. In Europe, Germany accounts for the most number of patents, with almost as many patents as Japan, which in turn is second only to the United States. However, filing activity in both of these countries is falling, helped by the fact that out of the total number of related patents filed, only one-quarter were filed in the last five years.

Although patent filings in 3D printing started about 20 years ago, this technology has yet to be fully commercialised. It is likely that the next few years will see the mass utilisation of key patents covering the domain of laser sintering – a 3D printing technique – on account of the majority of patents in this area expiring in 2014. Laser sintering is currently the least expensive 3D printing technology and can produce high-resolution 3D products that can be directly sold as finished goods. Aggressive patent filing activity in China may lead to further innovations in this technology.

Table 1 shows the white-space analysis of patents filings in important jurisdictions over the past decade. It demonstrates that 3D System Inc has filed patents in all important jurisdictions, followed by Stratasys Inc and Evonik. Stratasys has no patent filings in South Korea and the United Kingdom, while Evonik has no filings in the United Kingdom. Daimler and Siemens have filed patents mainly in three jurisdictions: the United States, Japan and Germany. These countries together represent the top three jurisdictions according to the number of filings. South Korea and the United Kingdom are the countries with the fewest filings by the top players. There is a huge white space at the bottom-right corner of the graph. Daimler and Siemens have very few filings in countries other than the United States and Germany. The Boeing Company, which has manufacturing centres across the United States for 3D printing aircraft parts, has the most number of filings in the country, but no patent filings in Austria, Australia and South Korea. The ExOne Company has filed most of its

Table 1. **Heat map for patent filings**

Total patents	Country/major assignee	3D Systems Inc	Stratasys Inc	Evonik	Daimler	Siemens	The ExOne Company	The Boeing Company	Materialise
424	United States	49	35	4	9	11	5	9	5
195	Japan	33	4	4	1	1	3	1	2
190	Germany	12	5	8	11	7	1	0	0
179	China	14	3	4	0	1	3	2	0
116	Canada	15	3	3	0	0	3	1	1
94	Australia	9	6	2	0	1	2	0	0
44	Austria	12	4	2	1	0	0	0	0
66	Korea	14	0	2	0	1	0	0	0
48	Great Britain	3	0	0	2	0	0	2	4
Total		161	60	29	24	22	17	15	12

patents in the United States, followed by equal filings in Japan, China and Canada. On the other hand, the company has not filed patents in Austria, South Korea and the United Kingdom at all. The overall white-space analysis could suggest a future patent filing strategy for companies.

Technology insights

Our analysts classified the 3D printing domain into different categories of 3D printing technique, modelling or scanning, quality check, printer devices and accessories, application and printer material. The category of 3D printing techniques was further broken down into five sub-categories:

- Light-based 3D printing – also known as stereo-lithography or radiation curing – is a relatively old technique (the first patent was filed in 1984) which involves using ultraviolet sensitive photo polymer resins as the principal material. A perforated platform is positioned just below a vat of liquid photo-curable polymer and an ultraviolet laser beam traces a slice of object on the surface of this liquid, thereby hardening a layer of the polymer. The perforated platform is then lowered very slightly, allowing a new layer to be processed, which is fused with subsequent layers. Since 2005 this technology has witnessed a significant rise in patent filings. Around 45% of patents based on this technique have been filed from 2005 onwards.
- In fused deposition modelling, a plastic or wax material is extruded through a nozzle that traces the cross-sectional geometry of the part to be manufactured in layers. The nozzle contains resistive heaters that keep the plastic at a temperature just above its melting point, so that it flows easily through the nozzle, while the substrate layer is kept cool enough for the molten material to solidify upon contact. An oven inside the printer preheats metal/plastic powder just below its melting point. Molten material is extruded from the nozzle and deposited on a layer. Subsequently, the platform lowers down to the next powder layer and the process continues. Patent filings have increased in this sub-category as well, with 57% of the 82 related patents being filed in the last five years.
- Sintering – an atomic diffusion-based process – uses powder as the raw material to create objects using 3D printing. A high-powered laser beam sinters the powder material layer by layer. The 3D object is made upon the solidification of the molten material. A total of 185 patents have been filed related to sintering so far, of which 46% were filed in the last five years, demonstrating an increasing trend for filing patents in this category.
- Lamination-based 3D printing techniques use sheets of paper, plastic or metal laminates with a polyethylene coating on the backside as the raw material, and laser beams to trace the desired pattern. The technology uses

Chart 3. **Patents according to 3D printing techniques**

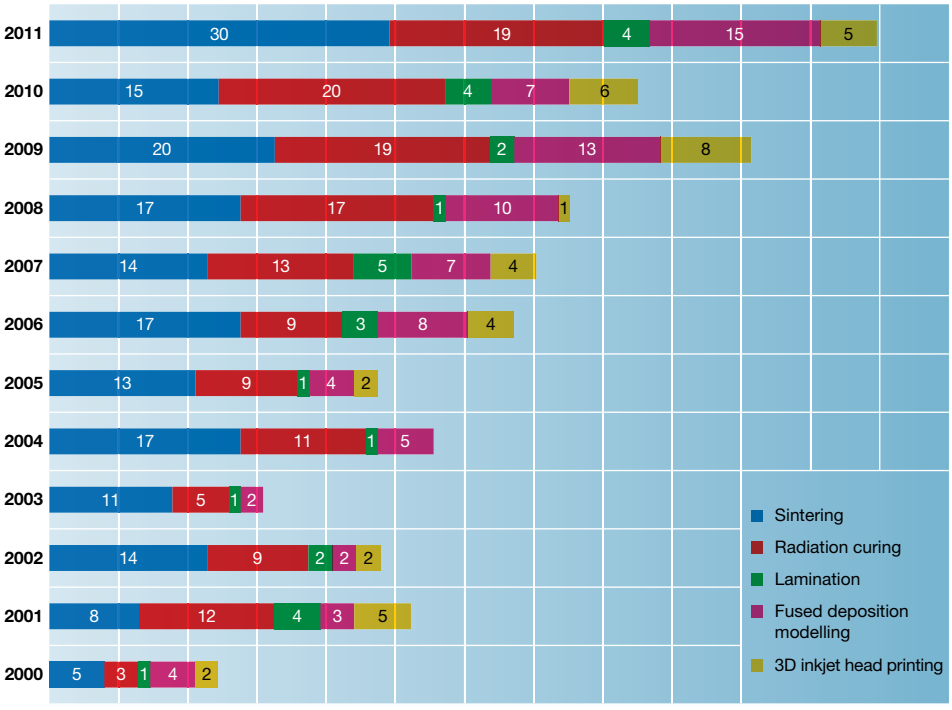
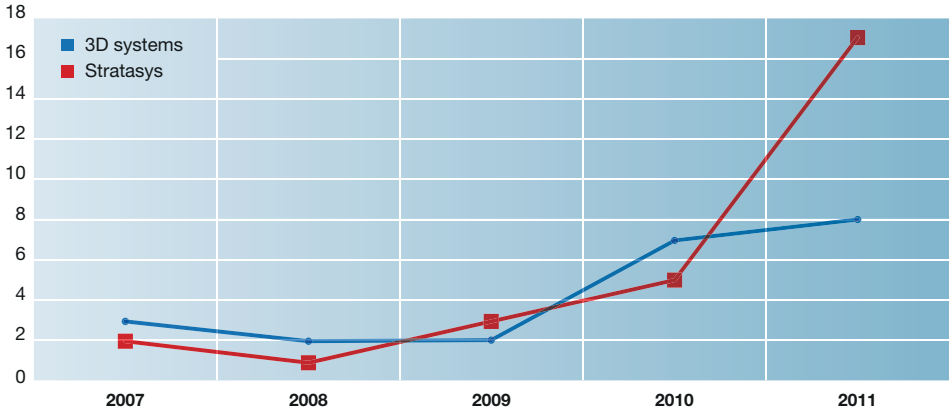


Chart 4. **Patent filings of 3D systems and Stratasys in the last five years**



Bio printing – human ear

Bio printing of living organs has a long-term potential to save or extend many lives. Patients may not have to wait for long periods for donated organs. The living organs can be 3D printed for the living tissues of the patient

Source: BNext – *www.bnext.com.tw/article/*

different colouring materials, which blend with the base material to give the object the desired colours. Printing may be carried out using an aqueous binder liquid to help the particles of polymers fuse with each other – organic or inorganic solvents are used. Compared to other techniques, far fewer patents have been filed in this domain, with only 6% of the total patent filings related to this sub-category.

- 3D inkjet printing includes an inkjet-like printing head moving across a bed of powder, selectively depositing a liquid binding material in the shape of the section. A fresh layer of powder is spread across the top of the model and the process is repeated. When a model is complete, the unbound powder is automatically removed. Since 2000 only 8% of the total patents filed related to 3D printing have been based on this technique, with the highest number of patent filings in this sub-category taking place in 2009.

Patent distribution by assignee

Two major corporations in the field of 3D printing are 3D Systems Inc and Stratasys Ltd. 3D Systems' portfolio has a total of 52 distinct patent families. The highest numbers of filings relate to categories of printing techniques and printer material, which account for around 85% of the total number of filings related to 3D printing technology. Under printing techniques, around 50% of patents relate to the radiation curing method of printing. However, in our analysis the categories are mutually inclusive. So a single patent can be categorised in multiple categories, depending upon its claims and specifications.

Stratasys' patent portfolio includes 42 patents. Among these, the highest number of patents filed (ie, 60% of its 3D printing portfolio) relate to the category of printing techniques, followed by printer devices and accessories, which represent about 55% of Stratasys' 3D printing patents. Under printing techniques, 38% of patents filed relate to the sub-category of fused deposition modelling. Stratasys has an almost negligible focus on the sub-category of sintering and lamination-based 3D printing. According to our analysis, 3D Systems Inc clearly dominated patent filings in the past. However, since 2010 Stratasys has filed almost twice as many patents as its main rival.

Among other major assignees, engineering and electronics conglomerate Siemens' patents disclose a wide range of applications for 3D printing. The portfolio holds 14 patent families in total. The company has filed eight patents related to sintering and nine related to radiation curing. Ten out of 14 patents disclose applications related to use in medicine and tools and machinery. Daimler 3D printing, on the other hand, has a portfolio of 11 patents, of which six relate to the sintering sub-category. Evonik and Boeing have nine patents each. Out of our dominant assignees, Siemens and Boeing are the only companies to file patents related to glass as their printing material. Chemical company Evonik has filed mostly in the 3D printing materials category, while Boeing has filed applications in the aerospace domain. Of the nine patents filed by Materialise NV, five relate to medical applications, while the remainder disclose tools and machinery applications. The company ExOne has six patents focusing on metals and alloys as printing materials.

Many important patents relating to laser-sintering printing techniques are set to expire in 2014. This presents a great opportunity for innovation and low-cost commercialisation using this technology. According to a report from McKinsey Group, when the original patent for fused deposition modelling expired in 2009, an open source project called RepRap created 3D printing systems based on the technique. This led to free availability of software and thus rapid innovation in 3D printing technology. A similar phenomenon is expected with laser-sintering technology post-2014, which would again lead to lower prices for 3D printers. China has cultivated a thriving home-grown industry in 3D printing and now supplies well-priced 3D printers throughout the world. In 2012 China's Ministry of Industry and Information Technology launched an initiative to invest US$80 million in 10 research centres devoted to 3D printing, as revealed by 3DP Industry Alliance at its third council meeting in Chengdu earlier this year.

The aggressive expansion and patent filing trends of top assignees in the last few years shows that 3D printing technology is well on its way to playing a major role in customised manufacturing and digital object storing in the near future.

Industry roadmap

According to Pete Basiliere, research director at US IT research and advisory firm Gartner, 3D printing is accelerating towards mainstream adoption. He suggests

Chart 5. **Patent filings of dominant assignees related to various technological heads**

that while the technology may not be affordable for everyone, it is within reach of most enterprises. Companies in this field would benefit from making the technology commercially applicable and more useful to consumers. A report by Gartner – "3D printers not made by hipsters in Brooklyn" – indicates that enterprise-class 3D printers will cost less than US$2,000 by 2016. In an article for *Tech Crunch* in March, senior editor Matt Burns argued that the current cost of 3D printing relegates it to the well-off hobbyist or successful small businesses. However, the Gartner report points that many difficulties still exist with the technology for enterprise printers. The obstacles that need to be overcome for large-scale adoption of 3D printing to take place include the following:

- There are many legal battles yet to be won before 3D printing becomes truly commercial. On May 2013, high-tech gunsmithing group Defense Distributed created the world's first fully 3D-printed gun, the Liberator. There has been much panic and cynicism about such uses of 3D printing and the world needs to prepare itself. Members of the New York City Council and a state assemblywoman have introduced two different pieces of legislation that would either regulate or ban the manufacture of 3D-printed guns, according to the *New York Daily News*. Council member Lewis Fidler, who introduced a bill for New York City, told the *News*: "If left unregulated, these would be weapons without histories – potentially no identifying marks or sales histories. We wouldn't even know these weapons exist, until they were fired."
- If 3D printing is going to revolutionise manufacturing, it must be present in the developing and populous BRIC nations at affordable prices. These emerging economies can act as engines of growth due to their rising middle classes, which can provide the required momentum to drive 3D printing. Although 9% of the patents in the field have been filed in China, there is a long way to go before the technology trickles down to the public.
- Even though the technology is at a nascent stage, 3D printers are journeying slowly towards the home and retail

Rocket injector plate
NASA has reduced manufacturing time and costs drastically by 3D printing such injector plates

Source: Wired Magazine – *www.wired.co.uk/news/archive/2013-04/16/f-1-moon-rocket/viewall*

Action plan

- The United States is the leading nation in 3D printing technology, followed by Japan and Germany. Recently, China and Canada have picked up the pace in developing this technology.
- Stratasys and 3D Systems are undisputedly the top companies in this industry, with strong patent portfolios.
- Key patents related to laser sintering technology are on the verge of expiry in 2014, opening the doors to new possibilities and opportunities.

Challenges ahead for the industry include:

- Bringing down the cost of 3D printers, as well as the materials used to print objects.
- Unrolling the technology while avoiding copyright issues similar to those faced by the music industry.
- Making 3D printers available in the developing world to help drive growth.
- Restricting the availability of designs/materials that can be used to make dangerous objects, such as guns.

markets, and will eventually look to become everyday home appliances. Thus, making building materials (polymers) and specialty agents (chemicals) safe for homes, especially homes with children, is essential. Some of the required regulations include food grade and fully cured (ie, no free radicals) plastics on completion of the build, non-hazardous inks and other agents which are disposable as standard household waste, as well as vapour-free, odour-free and leak-free operation and maintenance of the device.

- Similar to the personal computers of the 1980s, right now the cost of 3D printers puts them beyond the reach of most consumers. For these printers to become mainstream, manufacturers first need to make them affordable. Companies around the world have realised this and are working hard towards lower-priced models. "I think it's a combination of cheaper hardware, economies of scale and figuring out where to cut corners on low-end printers," editor of *MAKE* magazine Mark Frauenfelder told *ARS* magazine, pointing out that some of the newer low-end printers are using higher-quality ABS plastic (think LEGO). The main players in this domain should try to launch cheaper printers and plastics into the market.
- Similar to the music industry, there will be copyright issues related to 3D printing. Once a digital design is uploaded on the Internet, it can be printed anywhere around the world. Isabel Napper, partner at law firm Mills & Reeve and head of its technology division, suggests: "The UK has a huge history of innovative design. If we can create a sensible regime to deal with intellectual property rights in 3D printing, that would put us in a strong position." Issues will arise when people upload designs of objects without the required permissions.

The issues pointed out are not insurmountable, but they do require well-thought-out policies and regulations, along with the legal framework to allow safe proliferation of this technology.

Expect new developments

Studying the patents behind the working of personal 3D printers, commercial 3D printers and production 3D printers has revealed some surprising insights. There has been consistent research into the area of printing techniques, from stereo-lithography to fused deposition modelling and laser sintering. This suggests that we can expect further new developments, which would present even better techniques. Development in printing materials is also gathering pace, with the need for safer, more economical, more durable materials. New materials have been developed for use in various applications, such as biomedicine, aerospace and construction.

While the United States is the leading nation when it comes to advancements in 3D printing technology, other countries such as China, Japan and Germany are fast catching up. Unlike China, which is increasing the pace at which it develops 3D printing, Germany and Japan — among the leaders in patent filing a decade ago — are starting to fall behind. Similar inferences have been drawn about the corporate world as well, including M&A deals in the last few years.

Due to the nature of the industry, small breakthroughs and patent expirations could change the fortunes of companies and nations alike. For instance, the expiration of patents related to laser-sintering techniques is expected to propel innovation and further the technology. Development in biomedical materials is another important field which will help in bio-printing living organs, thereby saving the lives of millions who have to wait for donor organs. The next level of 3D printing is also expected to use liquid metal that solidifies upon extrusion. Drawing a comparison between how personal computers challenged traditional computing in the 1980s, advancements in 3D printing technology in the coming decade could provide the necessary push to make 3D printing a mainstream phenomenon. *iam*

Darshan Mujumdar is CEO of LexInnova, New Delhi, India
darshan.mujumdar@lexinnova.com