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Design for Rapid Manufacture: A Commercial Case Study of Security Equipment

Mike Ayre, Crucible Industrial Design

Biography

Mike Ayre is Managing Director of Crucible Industrial Design Limited. He graduated with a BA in Industrial Design from Sheffield in 1977 and then spent ten years designing products in Africa and Asia. Settling in the UK in 1987, Mike studied for a Masters Degree in Industrial Design at the Royal College of Art and established Crucible in 1990. Many of Crucible’s clients produce medical and scientific equipment, and the business has developed considerable experience of this sector with the design of commercially competitive, low-volume products.

Email: Mike@crucibleid.com
Web: www.crucibleid.com

Abstract

In 2004 Navtech Electronics approached Crucible Industrial Design for assistance in the design and manufacture of a new commercial radar system. The new product was intended to replace an existing system based on machined parts, and there was a four month window to bring a production representative version to the end customer. The resultant design was required to accurately position a number of moving components whilst the system underwent its operational duty cycle, remain portable, exist across a range of climatic conditions and achieve a cost reduction when compared to the existing concept. Target market volumes were to be 50 to 80 in the first year rising to 500 in the following year, with a 10 year product life cycle. The project has demonstrated the viability of SLS production components as integral parts in low volume, high technology products. The project has also explored some of the design requirements of SLS as a production process, particularly the need to optimise the efficiency of the build process and the benefits of taking advantage of the material properties offered by sintered materials.

Background
The production of low volume, high value equipment is an increasingly important part of the UK's manufacturing economy. This sector often represents the leading-edge knowledge that has become the UK's main competitive advantage. Navtech Electronics is a good example of such a company. It produces security products for specialist applications, primarily in aerospace and mining, which have to withstand heavy use and extreme environments. The technology is advanced, but production volumes are low.

Small batch production often results in high prices and can limit manufacturing options, and this has certainly been Navtech's experience in the past. Until recently, the company made about fifty systems a year using cast aluminium bases fitted with covers that were machined from high-density polyethylene. All of the internal components were also machined from stock aluminium and stainless steel, with the result that the products, though incredibly durable, were heavy and expensive to manufacture (see figure 1).

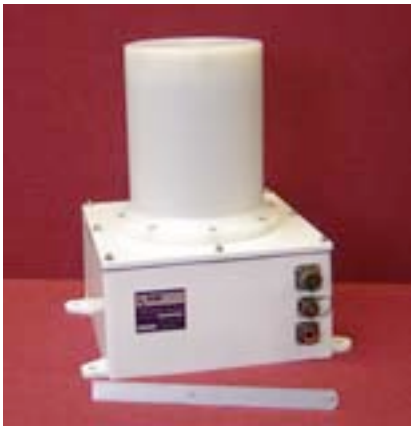

Figure 1: Earlier low volume product.

In 2004, Navtech decided to build on the success of its existing products by developing a new range of lightweight sensors aimed at a wider market. Although still low volume, with projected annual production of 200 units, the new products would need to use more economical methods to match the needs of the market. Navtech approached Crucible Industrial Design for guidance on the new products, and a design project was established in early 2005.

The overall brief for the project was to develop a new range of sensors that would be economically viable in small batches and be visually suitable for a wider market, including public spaces. The new designs had to utilise the reliable technology already developed by Navtech, and had to meet a number of strict performance criteria to allow the sensors to work effectively. Above all, the new products needed internal mechanisms that were extremely accurate and durable.

The Conventional Approach
Initial work on the new sensors focused on the main construction and engineering, which followed a conventional path. The internal structure of the product was changed to simplify the mechanisms, but most of the parts were still machined. In order to create design opportunities and reduce weight, the base was redesigned to be made in Glass Reinforced Plastic (GRP) instead of cast aluminium. The top, which had been the most expensive part, due to the amount of machining required,

now became one of the cheapest by producing it as a vacuum forming. Sealing the two main parts was achieved by a simple stainless steel ring that compressed two ‘o’ rings (see figure 2).

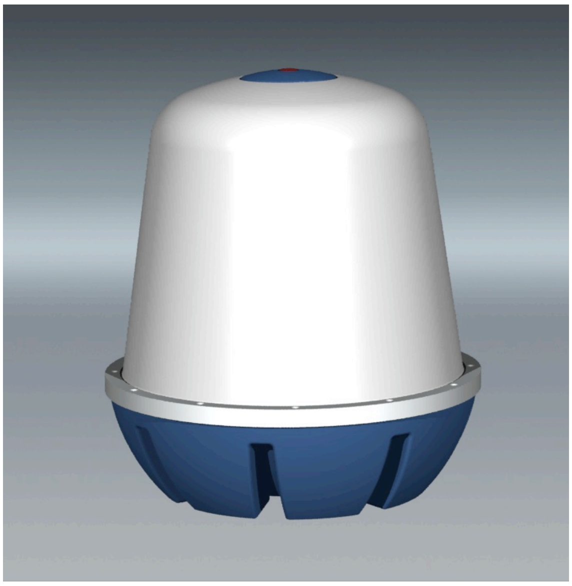

Figure 2: Overall view of new product.

So far, so good. However, one of the main challenges of the new design was the rotating sensor system, which was complex, but had to be lightweight and durable. Machining was a possibility, but would have been very expensive and heavy. Moulding would also have been possible, but would have been uneconomic at the volumes involved. A number of other routes were also explored, but all had serious disadvantages. This was the point at which the use of Selective Laser Sintering (SLS) was first considered for the manufacture of the part.

Initial Reasons for Looking at SLS
Crucible had used SLS in the past for model making and the production of functional prototypes, so understood that the process could be used to make durable parts. However, there were also a number of concerns, including:

- The unknown performance characteristics of the materials used.
- The repeatability of the process as a production method.
- The economics of the process.
- The long term performance of the parts in realistic use.
- The poor surface appearance of SLS parts when used as production parts.
- The absence of any design rules for the use of the process as a production method.

Despite these concerns, SLS looked like a good route to explore, simply because the parts would be internal, so surface finish would not be a major issue, and the complexity of a machined or moulded alternative would probably make sintering more economical.

Initial design work focused on establishing the basic economic and technical viability of the approach. The fundamental issue was clearly the efficiency of the SLS ‘build’, and studies were carried out into the basic geometry of the parts needed and the available production platforms.

The first area of study was the effective use of the 'layers' that make up any rapid prototyped part. This involved looking at efficient use of the build volume and the strength of the parts. The parts that made up the rotating system were developed to be as 'two dimensional' as possible so that they could be layered or stacked within the volume of a build. Next, the orientation of the build was examined to maximise the likely strength of the components. Given that the geometry of the parts was very narrow in places (see figure 3) it was decided that the parts should be made lying horizontally, as the build layers would be along the axes of the thinner areas, not perpendicular to them. To use what may seem an inappropriate analogy, the designers wanted the 'grain' to be running in the right direction. Given the anisotropic characteristics of SLS parts, this is not as odd as it sounds, and — as will be seen — not the only example of sintered parts mirroring the properties of more conventional materials.

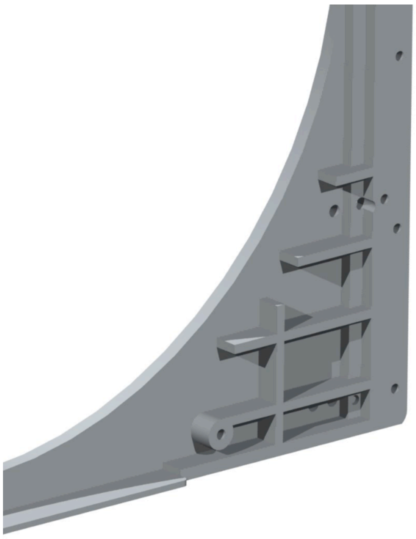

Figure 3: Thin sections of the main component.

Once the basic geometry was established, the designers looked at the space needed to build the parts horizontally, and which production platforms offered a suitable match in terms of production, and therefore cost efficiency. These studies all pointed to the EOS P700, as the twin laser platform provided the correct footprint for an economic layout of the parts. As one of the few operators of the P700 at the time, detailed discussions then took place with 3T RPD in Newbury. These discussions resolved the fundamental economic viability of the parts, and allowed more specific technical research to begin.

The design of the sensor components was then developed in more detail, and test components built to establish the basic durability of the design and the approach. These tests included identifying the stiffness, breaking strength and temperature performance characteristics of the parts. As there is so little data available on material specifications for SLS parts, these tests were empirical, and based on placing the parts in extreme versions of a normal operating environment. The tests were successful, and also led to unexpected material properties being identified that suggested more adventurous design possibilities.

Beyond Material Substitution

The durability of the SLS parts used in the initial trials suggested that the process would enable Navtech to build in new features at little additional cost, given that they would be within the existing build envelope. The primary new feature was the introduction of a moving arm that would enable the sensor array to be moved up and down (see figure 4). This, in turn, suggested the possibility of not only building the moving arm ‘in situ’ within the part, but also building in the bearings as part of the SLS structure.

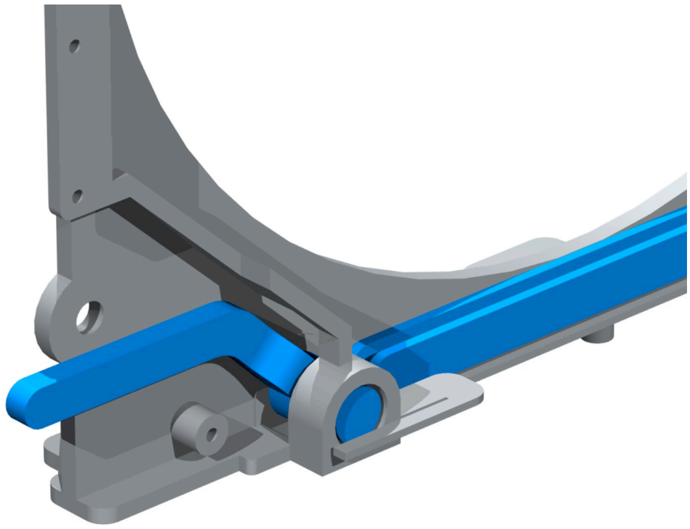

Figure 4: Pivot arm built ‘in situ’.

Building the arm in place worked well, but the integration of SLS bearing surfaces was not wholly successful. The need for reasonably thick sections within the lifting arm resulted in powder fusing in what should have been the gap between the pivot and the inside of the bearing surface. This was caused by a twelve degree difference between the temperature in the pivot and the surrounding area. In another area of the pivot arm, significantly thick sections positioned next to thin sections caused distortion as higher heat levels and slower cooling caused distortion to the thinner sections. In the same way as the parts are ansiotropic, and therefore have a ‘grain’, so they cannot be built regardless of section. The result can be similar to the sink marks caused in injection mouldings when dissimilar wall sections are used together. Unlike sink marks in mouldings, however, dissimilar wall sections can be allowed for in the build process — provided the composition of the build is the same every time.

The durability of the SLS material did, however, allow the creation of built-in springs. Thin sections were introduced at the top of the sensor support to guide and return the sensor array after it had been lifted by the arm. This possibility had not been identified until the material properties were examined in detail, and created a new feature that would have been expensive to produce by more conventional means. The pivot arm bearings also benefited from an ‘SLS spring’ (see figure 5).The conventional plain bush that provided the bearing surface was held in place by a strip of SLS material that could be pushed aside when the bushing needed to be replaced. Again, this removed the need for conventional brackets or clips, and any additional assembly work.

The addition of these features and capabilities added two new factors to the concerns about the use of SLS as a production method — fatigue and wear. As with all performance characteristics of the materials used in the SLS process, data on these issues is virtually non-existent, so Navtech began a programme of testing detailed prototype parts over an extended period.

The main components were mounted to a rigid test rig, and then fitted with a powerful solenoid that would make all the moving parts operate through their full range three times a second. This was approximately four times faster than the normal operating speed. This test rig was then left running continuously for two months. This equates to approximately fifteen million cycles of the components. The main issues that these tests examined were the reliability and wear of the bearings fitted to the SLS pivot arm; the wear between the solenoid cam and the pivot arm; the wear between the polycarbonate sensor window and the pivot arm; and the action of the window on the SLS guides that locate it.

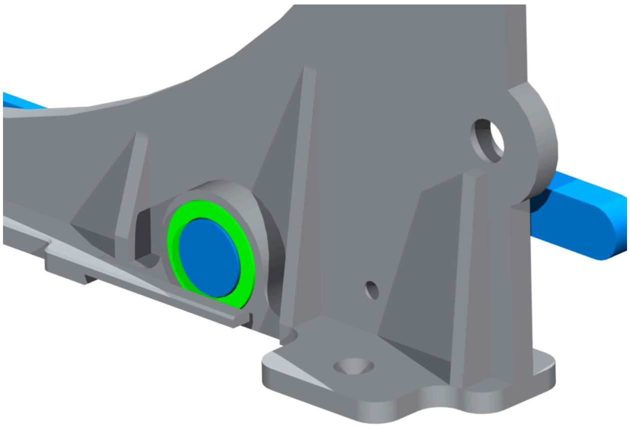

Figure 5: Pivot arm bearing and sprung retaining clip.

The results of the tests were extremely positive. Very little wear was recorded to any of the parts, all of which functioned almost perfectly at the end of the test. The bearing surface between the aluminium solenoid cam and the pivot arm became highly polished within a few hours, improving efficiency and suggesting that the friction had created a form of 'work hardness' (see figure 6).

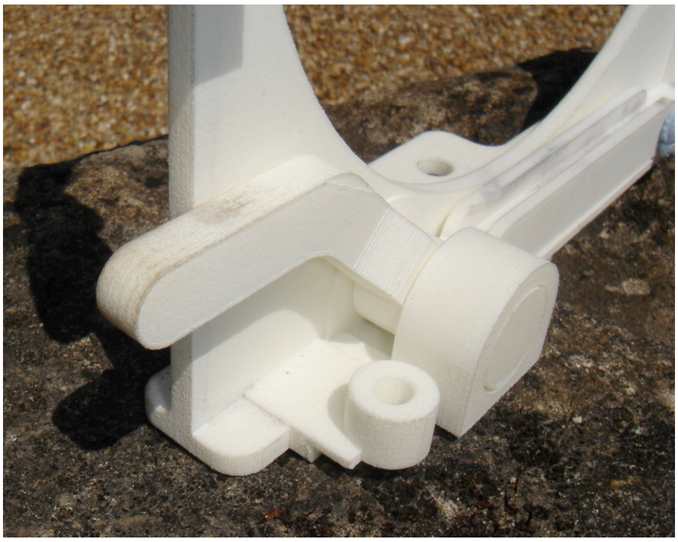

Figure 6: SLS pivot arm and solenoid bearing surface after tests.

Once the tests had indicated that the parts were mechanically and technically viable, detailed work was carried out on optimising the build efficiency to minimise cost. Initial studies with the P700 had indicated that the build envelope would be suitable for the Navtech parts, but further work was now carried out to see if it would be possible to nest parts very closely (see figure 7). The results of these attempts were not successful, as the temperature and cooling characteristics of individual parts affected those next to them, causing quality and distortion problems. A more effective layout was eventually developed, allowing a good balance between production efficiency and the cost of the parts.

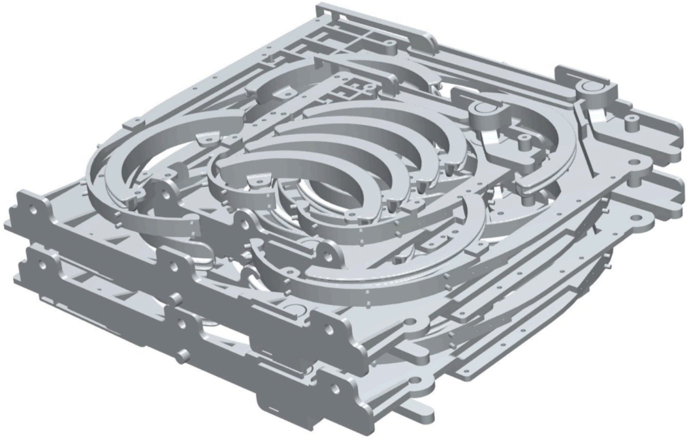

Figure 7: Complex attempt at build efficiency.

Moving Towards Production

As has been seen, it is wrong to assume that the build envelope of a sintering machine can be filled to capacity with objects of any wall section, volume and orientation, and obtain consistent results. This is one of the main differences between sintering as a prototyping process and its use in production. In prototyping, the build is made up of parts with dissimilar designs and sections, and economics dictate that the space has to be used as efficiently as possible. In production, the repeatability and consistency of the parts is critical.

In considering the production of parts for Navtech, therefore, a number of issues had to be considered:

- The orientation of the parts had to be kept the same, to maximise the chances that the lasers would produce consistent results. This was true for both the basic layout (horizontal) and the relative rotational position of the parts. Each build would also need the same layout, so any thermal effects caused by the proximity of another component, for example, would be consistent.
- The parts were arranged so that they did not cross the line between the two sides of the build chamber. Given that the lasers in a P700 are operating in an ‘open loop’ it is impossible to guarantee identical performance on both sides of the chamber.
- The thermal and cooling regime had to be kept as consistent as possible between builds to ensure that parts were made under controlled conditions.
- No other ‘build fodder’ can be included in a production build, or the thermal and cooling regimes will not be consistent.
- Under no circumstances can a build be paused to add another part — the results can be disastrous, as weaknesses can be introduced that will ruin the entire build, not just one part.

Once all these issues had been considered and worked through in tests and trial runs, the new products were ready for manufacture. Production is now underway, and the first units have been supplied to customers in the USA and Europe.

Opportunities and Threats

The use of rapid manufacturing techniques offers tremendous opportunities to designers, particularly when working on complex equipment that has to be made in small quantities. The ability to build multiple functions into one component — in ways that would be totally uneconomic or impossible using conventional methods — offers real competitive advantages. This is further enhanced by the material properties of the sintered materials, which can add more functionality to a part. Somewhat ironically, these benefits can only be fully realised if some basic design and engineering lessons are temporarily forgotten. Draft angles; the ability to fully dismantle a set of parts; some aspects of the nature of wall sections — all of these should be put aside if sintered parts are to be used to their full potential.

However, the idea that 'anything goes' is surprisingly inaccurate. The effective use of rapid manufacturing techniques is governed by a set of rules that appear to have come from a parallel universe — they are different, but strangely familiar. Thick wall sections next to thin ones can cause problems; the nature of heat build up during the cooling process is key in controlling distortion; the build orientation of a part can critically control its strength; and dissimilar sized parts cannot be placed close together.

The most fundamental issue, however, remains the efficiency of the build. In an ideal world, a single build would be made up of parts that cool at the same rate across the entire chamber, top to bottom, side to side. Not only that, they would all be orientated in the same direction and utilise the build layers to provide maximum strength to the parts. Given the limited size of build chambers, this requires designers and rapid manufacturing suppliers to work very closely together if they are to create parts that work and are economic. The technical limits on the design need to be understood at the concept stage, so that assemblies can be designed in the right number of parts, at the right size and in the correct orientation. This will require a shift of approach for some designers, but will create interesting creative and engineering opportunities for others.

A similar shift is needed in terms of ordering parts. Efficient production quantities need to be based on what the equipment can produce, not nominal figures like fifty or one thousand. Depending on the layout and build regime for a given part, an efficient batch size might be twenty-three or one hundred and fifty two. Economics apply to the quantities that can be ordered as well. It is a popular idea that rapid manufacture means that you only have to buy the parts exactly when you need them, which is possible if you do not mind paying prototype prices, but to take advantage of the economies of scale, it is necessary to order a complete 'build' of the parts, and this may run into hundreds of components.

Finally, more information is needed on the technical performance of materials used in rapid manufacturing processes. At present, the possibilities and limitations of such materials can only be discovered empirically during individual projects. The true potential of these processes will only become clear when the manufacturers provide more data, allowing designers and engineers to push the technology and commercial opportunities to the limit.

The Potential for Specialist Manufacturers

Navtech made a bold move when it agreed to look at SLS as a production method for its new range of security sensors. The company's conclusion is that the approach has been the correct one, and that it offers far more scope for innovation than was originally thought. The new design is dramatically less expensive to produce than the original product, and the technology has allowed the company to introduce new features that were not thought possible at the outset. Far from simply being another way to make a set of parts, the whole concept of rapid manufacture allows Navtech to continuously improve its product without paying any tooling or set-up penalty. The challenges now are to define new design methods, identify material properties in a much more comprehensive and useful way, and develop improved methodologies for maximising production efficiency. Once these issues are addressed, rapid manufacture will deliver the kind of competitive advantage that small high technology companies need to stay at the forefront of innovation and design.