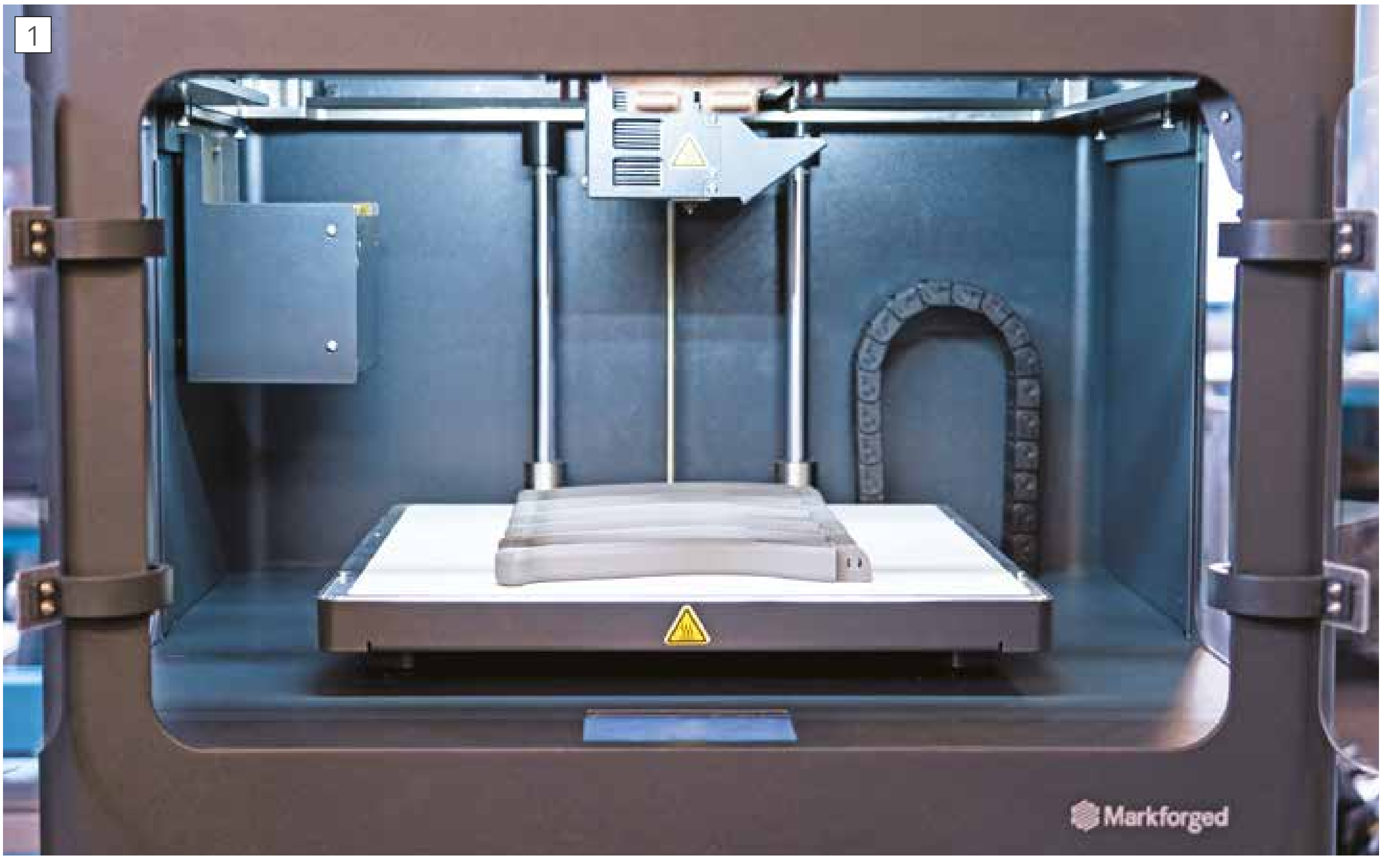
3D Printing Takes to the Air!

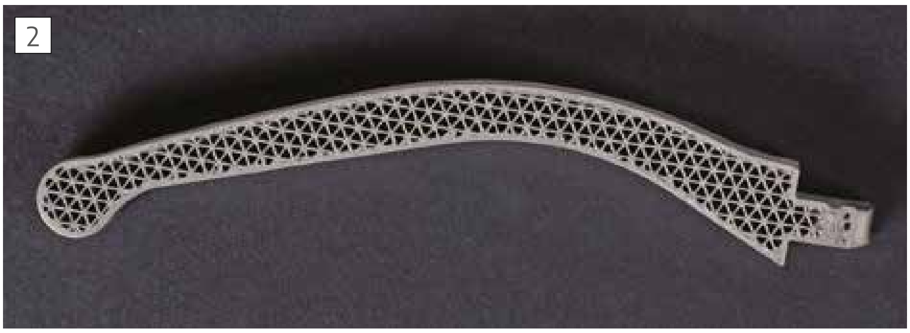
Mark Noel explores the boundaries of what can be achieved with 3D printing in the home workshop.



Markforged 3D printer. Parts are laid down as a matrix of steel powder and resin, then sintered in an oven to leave the metal component.

For a while I had been watching clever people building Reprap 3D printers from a web of cogs, rods, belts and Meccano. Along with most MEW readers I was committed to subtractive machining, whittling away stock materials with my lathe, mill and hand tools to create various contraptions. Tinkering with 3D printing looked like fun but surely printing door knobs and dinosaurs was a distraction from proper engineering?

But then I was asked to review Neil Wyatt's splendid book *3D Printing for Model Engineers* which opened my mind to other possibilities, such as the tools and fixtures, clamps, gears and other widgets that proved useful in his workshop. In this new era of additive machining parts were being created



Stainless steel motorcycle handlebar brake lever printed in a Markforged machine.

constructively, layer by layer, in a wide range of materials.

The possibilities were highlighted when I attended the Mintronics-GoPrint3D demonstration day in 2018, where an impressive suite of printing technologies were on display, as I reported in MEW 269. Machines from Markforged, Formlabs, Ultimaker and Zortrax were busy fabricating precision parts in plastic, carbon fibre and even stainless steel, some examples of which would be challenging to make using conventional methods, **photos 1** and

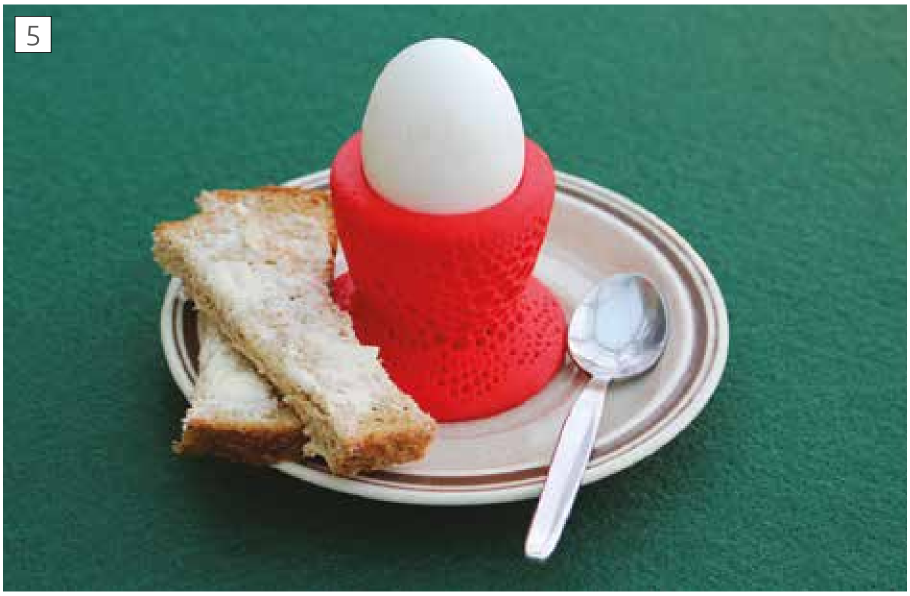
Formlabs Form 3 SLA type printer with their Wash and Cure machines.

2. The experience was a revelation, and now seemed the time to jump in, but how? There exist only two technologies that are really affordable to the hobby engineer, namely Fused Filament Deposition or FFD, and another process in which liquid resin is solidified by a laser. The experts at GoPrint3D suggested that FFD was now a fully mature technology that had attained limits of resolution and accuracy, while the laser process was (and still is) developing at pace.

FFD printers make the part by extruding a fine molten strand of plastic that builds layers defined by a sophisticated slicing program. In some machines layers can be as thin as 0.1mm, with strands as narrow as 0.25mm, and in a range of pliable or rigid plastics, the most common of which is the hard polymer PLA. Any parts which have steep overhangs must be supported to prevent collapse during printing, and this can be accomplished either with a scaffold of the same material, a brittle 'breakaway' plastic or with PVA which is dissolved away from the finished print in warm water. Most FFD printers drive the plastic stock (in the form of a cord) through a Bowden Tube via a motor-driven feeder behind or inside the printer. In contrast Direct Drive printers incorporate this feeder assembly within the moving extruder head in an effort to achieve greater part accuracy, although the increased inertia can slow the part's build. Whichever configuration is employed it is obvious that two extruders are required to lay down structural plastic plus soluble PVA or a breakaway support material.

Printers that polymerise liquid resin to build solid parts also need to support steep overhangs but these scaffolds are grown from the same resin within the one polymer tank. This technology has developed along two competing lines, each with pros and cons and with marked differences in cost. The original (and still current process) is Stereolithography (SLA) in which a set of moveable mirrors scans a narrow UV laser spot over the surface of the liquid resin, 'writing' it into a solid pattern in each layer as the build platform is lowered. The Form 3 printer is an example of this type, **photo 3**. Recently a simpler process has been developed in which these mirrors are replaced by projecting ultraviolet light through a high-resolution LCD which acts as a programmable mask to expose and solidify a complete layer almost instantly. In such Masked Stereolithography Apparatus (MLSA) the print resolution (or size) is limited by the LCD's pixel density, but such machines are cheaper and thus more accessible to the hobbyist. The Prusa SL1 is an example of this second type of machine. (M)SLA type printers can achieve almost flawless prints with layers as thin as 25 microns. However, this process has several downsides that have discouraged uptake in the hobby community. First, the resins are expensive and can decompose in air if left standing for a long time between prints. Secondly, unpolymerised resin must be removed from parts by washing in isopropyl alcohol. Third, there must be no closed cavities in the part that will seal uncured resin and, finally, prints must be cured in a UV chamber or in sunlight to achieve peak strength. Some manufacturers have simplified this workflow by providing

Ultimaker 3 Extended printer. This uses FFD technology and twin extruders.



Egg cup designed using Alibre, latticed with Meshmixer, printed in an Ultimaker 3.

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A selection of gauges printed to determine optimum sizes to incorporate in particular design models.

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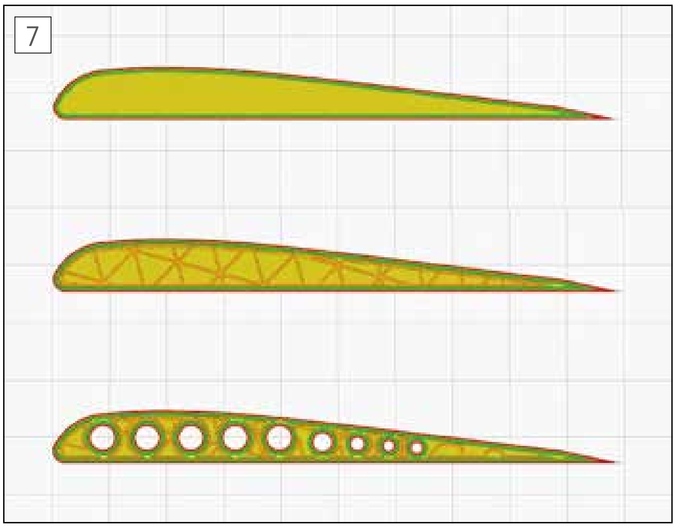

Efforts made to lighten a 100mm long wing rib by adding holes do not always result in less weight as shown in this example. Top 1mm thick, solid = 1 gram. Centre 5mm thick, 20% fill = 3 grams. Bottom 5mm thick 20% fill with holes = 3 grams, i.e. no lighter!

separate or combined wash and cure machines, but still there remain the issues of high running cost and material waste. The Resources section at the end of this article lists several popular printers incorporating the technologies reviewed here.

It is worth highlighting a marked difference in performance between FFD and laser technologies when it comes to printing multiple parts. To extrude 10 copies of a component in an FFD printer will take more than 10 times longer because of the extra movements of the extruder between the several parts. On the other hand (M)SLA printers take the same time whether building 1 or 100 parts because the time to expose each layer is fixed. This consideration might be decisive if choosing a printer whose main task will be to replicate numerous objects such as model railway sleepers, wing ribs, wheel spokes, tank tracks or war games characters. Again, a winning feature of this technology is the extreme resolution possible, such that surfaces appear virtually smooth.

Having made the decision to begin printing dinosaurs (or not!) I recognised that FFD was the logical entry point for me. GoPrint3D (now Additive-X) pointed to Zortrax and Ultimaker as makers of reliable machines based in Europe, although both had premium price tags. By selling my wife for medical experiments I secured enough funds to purchase an Ultimaker 3 Extended, a dual-extruder machine with a generous print volume, **photo 4**. The shipment included reels of Ultimaker's PLA, Breakaway and soluble PVA materials, plus two 0.4mm diameter extruders.

Of course, I do recognise that many relish the challenge of building their own printer either from a kit or from parts available from specialist suppliers, as did Mr Wyatt. Instead, my focus has been on acquiring design skills that lead to functional parts, taking the view that I do not want to *build* a kettle to boil water; I would rather *buy* one to make the coffee.

A huge variety of print-ready solid models created by talented folk can be downloaded free from the Internet. As I will show later my needs are rather specific and not fulfilled by free part-models. These must therefore be generated from scratch, with core software tools being FastCAD for 2D drawing and Alibre Design for 3D modelling, with occasional use of Meshmixer to create lattices from 3D solid objects. Finally, Ultimaker's remarkable Cura program converts these solid models into printer instruction files.

Having installed the machine, my very first creation was an egg cup created from a revolved solid in Alibre, pierced using Meshmixer. The egg was extruded by a hen. With buttered soldiers it provides a nourishing start to the day, **photo 5**.

Some Comments on Precision and Accuracy

Textbooks advise that Engineering Precision reflects the ability of a process to reproduce parts that are dimensionally consistent, while

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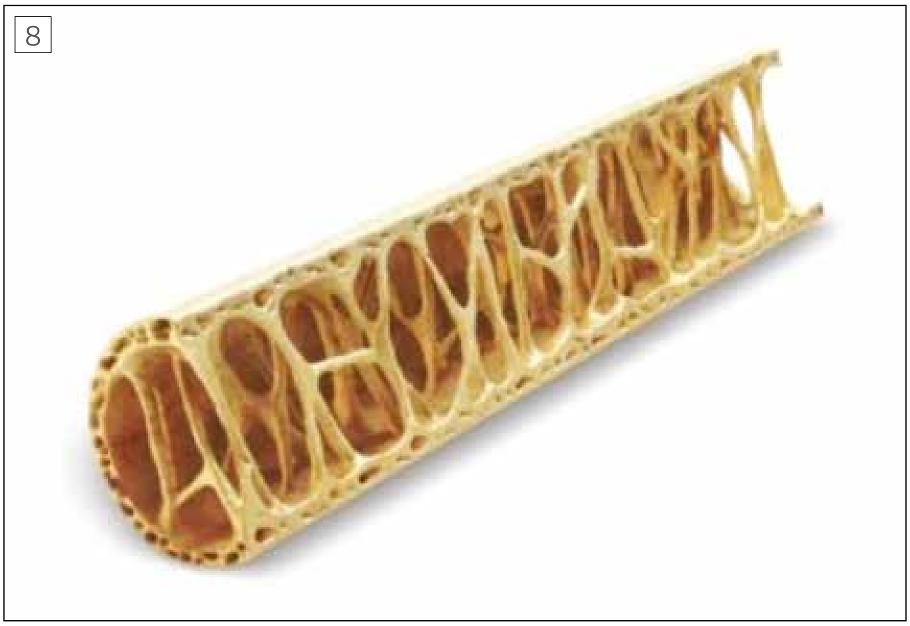


Example of a hollow-latticed bird bone that combines strength with low weight.

Engineering Accuracy expresses the extent to which dimensions in a finished part match values in a specification.

In model engineering we are largely concerned with Engineering Accuracy since we usually want one part to fit with another. On the other hand a consistent departure from accuracy with sufficient precision is often acceptable when creating assemblies such links for the tank tracks or railway sleepers mentioned earlier, where small inconsistencies do not affect aesthetics or function.

A recurring issue with FFD printing is ensuring accuracy in the printed part, since dimensions vary according to material choice, print speed, temperature, layer height and nozzle diameter. My solution to this dilemma is to always use Ultimaker Tough PLA with a 0.4mm extruder, and to accept Cura's default print speeds and temperatures. Then the only variable is to alternate between layer heights of 0.1 and 0.15mm depending on the desired surface quality.

As the material extrudes and adheres to the underlying layer it swells and slightly enlarges the horizontal dimension. Cura can compensate for this to some extent with the 'Horizontal Offset ' function but the tolerancing still falls short when a snug fit is needed in a recess for a ball bearing for example. My solution has been to print sets of stepped gauges with sizes defined in CAD models. Then the printed gauge size that exactly fits the target object (e.g. a metal shaft) is incorporated in the object model. Several gauges produced for specific projects are shown in **photo 6**.

Model aircraft built using printed parts and carbon fibre.

Left, 1943 Gibson Girl kite and right, 2021 Gibson Boy.

Some Comments on Strength and Weight

As this article's title suggests, I use 3D printing to create gadgets that take to the air, and therefore every design aims for a compromise between strength and weight, with aesthetics sometimes being a factor. Surprisingly, the experience of merging solid modelling with 3D printing soon produces a marked change in mindset away from the subtractive machining experience, where formerly one would think:

"How can I design a part that can be made with the tools that I have?"

to:

"What would I like to make given the freedom that I now have?"

3D printing software provides new opportunities for distributing load within a part by configuring light internal mesh structures that are usually impossible to create with subtractive machining. This can result in significant weight savings over a solid object but, nevertheless, care is needed when trying to lighten things still further by adding holes. This is demonstrated by comparing various designs of the wing rib shown in **photo 7**.

Thickening a solid rib to increase stiffness clearly succeeds at the expense of weight. Since bending stress is confined largely to the skin, stiffness is largely maintained by instead filling this thicker rib with a hollow lattice, which significantly reduces the weight. However, when an attempt is made to reduce weight still further by piercing this rib with holes there may be no further reduction in weight. This is because each hole is circumscribed by a skin with mass equal to (or sometimes greater than) the mesh it replaced! Hence experimentation is required to make a light part fit for function and our birds have solved this problem by growing hollow-latticed bones using 3D osteoblast deposition technology or ODT, as seen in **photo 8**.

Ultimaker's Cura, Zortrax's Z-Suite and other slicing softwares include numerous

Top: Details in the frame of the Gibson Girl kite. Bottom: details in the frame of the Gibson Boy.

configurations for infill geometry, while specialist programs can predict bending and buckling strengths in such complex structures. n-Topology is possibly the most advanced public code that combines design and analysis of optimum mesh structures. However, if like me, you are not a power-user, then FreeCAD includes a stress-strain analysis 'Workbench', while a similar module is available for Alibre.

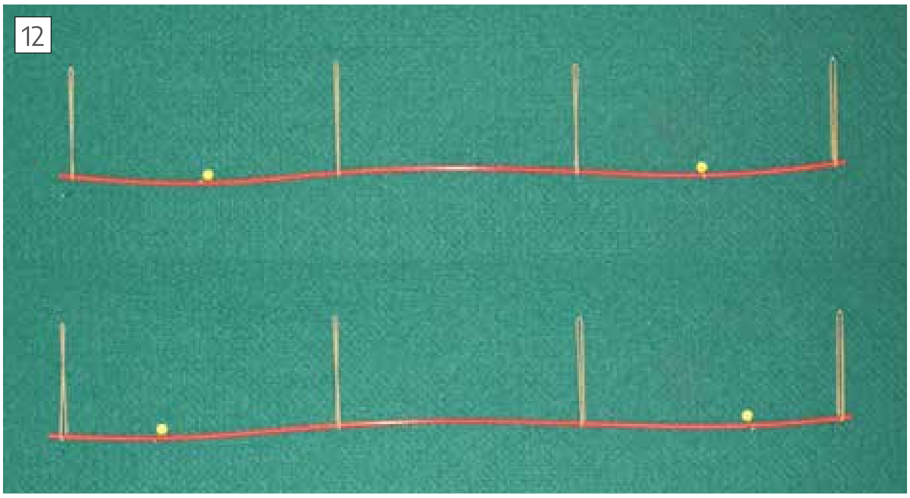
3D Printed Flying Machines

As a small boy and the son of an aviator, I was immersed in a world of aeronautics and was hugely excited on hearing that a Frenchman had just flown across the Channel. Mon dieu! The rotter!

The potential of 3D printing rekindled my interest in flying machines and led to me building the RC model aircraft shown in **photo 9**. Rather than use balsa and doped tissue, this aircraft incorporates pultruded carbon tubes for spars and longerons, PLA for ribs and bulk heads, with Oracover film over the flying surfaces. This aircraft as fully modelled in Alibre and assembled on jigs that were also 3D printed. Being my first attempt, it has turned out too heavy to stay airborne at anything below Mach 3 but the experience provides pointers to making lighter designs in future.

As a child R.A.F. stores provided me with all sorts of toys with which to tinker, including gyroscopes, radar sets and motors. However, the most precious item was an original, unused, Gibson Girl kite made by the Bendix Corporation in 1943, of which an estimated 13,000 were made, **photo 10**. These were installed in Bomber Command dingys, the idea being that downed aircrew could fly a radio aerial to sufficient height that rescue teams could find them. The kite is 3' tall and stows in a metal canister, together with a length of line, with printed instructions on how to assemble and launch it. The kite is extraordinarily well designed and constructed of the lightest materials available at the time, and it is clear that Bendix must have anticipated a massive wartime demand when you see evidence for their investment in the specialist tooling needed for mass production, **photo 11**.

The kite frame comprises ⅜" aircraft-grade aluminium. The structure splits into equal halves with the joints swaged and butted to click securely into place, and the two sails are sprung taut by over-centre 'spiders' with custom stampings and forgings in light alloy. The 8 hinges are actually soldered in place, a process that I thought had only recently become



Simulated scale model of the Bending Beam Problem addressed by Bendix in order to optimise the frame shape in their Gibson Girl kite. In this model the beam is represented by a flexible red PVC rod; elastic bands represent the tension forces exerted by the sail's seams, and the yellow pins represent the points where the spiders attach to the beam. Top: bending which occurs when the attachments are midway between the seams. Bottom: bending which occurs when the attachments are shifted outwards to the same relative positions as in the Gibson Girl kite - this forces a better aerofoil profile to the sails.

Replica of the Bumblenaut sub-orbital space capsule. Notice the retro rocket and high resistance handle. On loan from the Space Pioneers Gallery of the London Science Museum.

possible for light alloys. A glance at the spider's position reveals that the hinge connections to the longerons are not at the midpoint of the sails, as you might expect, but are positioned outboard in order to force a more aerofoil camber to the sails. This is demonstrated in the scale simulation of **photo 12**.

Airbase stores kindly gifted me 1km of braided nylon line, all of which was deployed one day to loft my kite above R.A.F. Wattisham. Eventually this was spotted on radar and all Lightning fighter aircraft were immediately grounded until the Military Police

Replica of the capillary-bubbling altimeter. As the unit ascends air expands from the larger reservoir through the narrow tube and bubbles into water contained in the smaller reservoir. During the descent water is drawn up the tube to a level that records the peak altitude. Patent Still Pending.

discovered the pilot (aged 8) lurking in a garden of the Officers' Married Quarters.

Around this time space exploration had become the New Frontier and I joined the cosmic race by building a

Carbon-nylon composite spider hub printed by Additive-X in a Markforged machine. An aluminium disc is bonded to the centre to act as a hard bearing plate for the ends of the spider arms.

Alpine Delta Conyne kite by Into the Wind, USA.

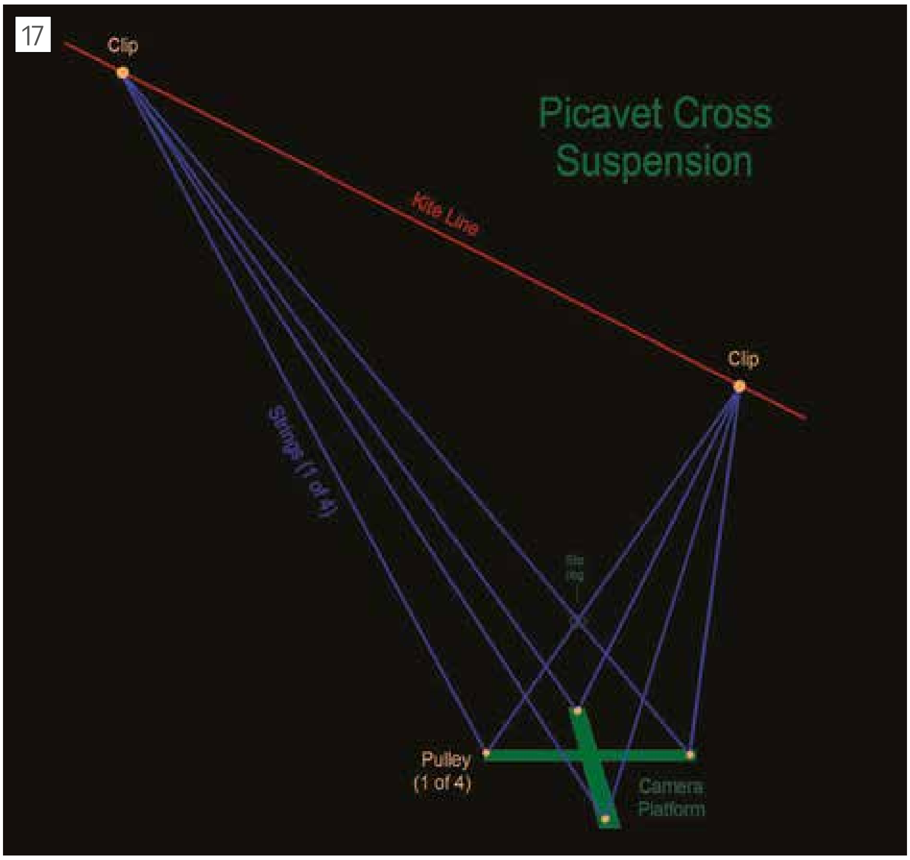
prototype capsule for launch on a sub-orbital flight aboard the Gibson Girl. An exact replica of this module is shown in **photo 13**. It was equipped with a viewing window, retro rocket, escape hatch and a blob of space-certified honey to nourish the Bumblenaut whom I caught, briefed, and ushered into the capsule. The unpressurised vehicle was drawn up the line by a drogue chute on a slip ring and the peak height recorded by my own design of capillary-bubbling altimeter, a replica of which is shown in **photo 14**.

Only one flight took place and the media (my Dad) gathered at touchdown to discover that the bumblebee had ejected safely and had returned to Mission Control in her hive.

Just like me, the Gibson Girl has become a fragile antique - tired, faded and rather ragged (witness author's picture). Not wishing to fly it any more, I set about designing a 1m tall replica using modern composites, 3D printing and light nylon fabric, to be called the Gibson Boy, as seen in photo 10. A full Alibre model of the frame was designed using 5mm carbon tube for the longerons and 3mm tube for the spiders. Aluminium clips to tether the sail to the frame were cut and shaped from 6mm OD aluminium tube. Outermost spider hinges and line tether points were printed in Tough PLA, with brass pins for all pivots, photo 11. A critical factor is to choose an over-centre angle of the spiders that ensures good sail tension without collapse of the mechanism under aerodynamic forces, and an angle of 3º was found to be satisfactory. The 4-way spider's hub is the most highly stressed component when the sail is tensioned, and for maximum strength these were printed in nylon-carbon composite by Additive-X using a Markforged machine. The resulting parts are about 3x stronger than if made of Tough PLA and have impeccable surface finish as seen in **photo 15**.

Sewing the sail was an unusual departure for this hobby engineer and it proved challenging to cut the precise lengths that ensured optimum tension when the spiders were sprung. The fact that Gibson Girl sails could be stitched consistently and taut in huge numbers is evidence again for major tooling investment by the Bendix Corporation.

My two box kites provided a springboard to the fascinating hobby of Kite Aerial Photography (KAP) which unites interests in design, engineering, electronics, meteorology, video and of course 3D printing. In contrast to flying a consumer drone for imaging, KAP provides genuine opportunities for innovation, particularly with regards to camera stabilisation and control. Of course, a drone is more maneuverable and can provide GPS navigation and astonishing camera stability, but flight durations are limited (~25 minutes) and the firmware enforces a limit to the peak altitude. Kites on the other hand can climb higher (the record is 16,038 feet), lift greater loads and fly for as long as there is a breeze. For the worldwide KAP community it is these factors that make



Picavet Cross type of suspension.

the hobby attractive.

My 'lifters' are two 9-foot span, framed delta kites - known for their steep flying angles and heavy lifting potential, such as my 9' span Delta Conyne seen in **photo 16**. Because kites swerve as the wind changes direction it is common practice to attach the camera gear 20-30m down the line where the catenary is more stable. Of course, anything hanging from the line is free to swing in the horizontal plane unless steps are taken to dampen this movement. Alternatively, the suspended camera can be mounted in a device that somehow maintains a constant bearing. Either or both of these approaches are commonly used.

A New Type of Camera Suspension

Most KAP enthusiasts suspend cameras using a stabiliser invented by Pierre Picavet in 1912. The payload is attached to a cross-shaped platform with pulleys at the four corners, from which strings extend to clips on the kite line as shown in **photo 17**. The geometry is such that the platform settles horizontally under the force of gravity, but it is prone to spin since there is no rigid connection to the taut kite line. Also, the platform remains free to swing about a horizontal axis, although aerodynamic damping can control this movement to some extent.

After 119 years it seemed time for a rethink and this led to my Aeronaut Suspension which is easy to rig, compact and provides excellent stability. It incorporates only two pivots and is built of stiff carbon fibre and 3D printed parts, **photo 18**. It is effectively a twin-pulley parallelogram which ensures that a camera fixed to the lower pulley maintains a fixed angle to the kite line, as shown in **photo 19**. The taut line generally provides a more stable reference for a suspension than the 'effective gravity' seen by a Picavet.

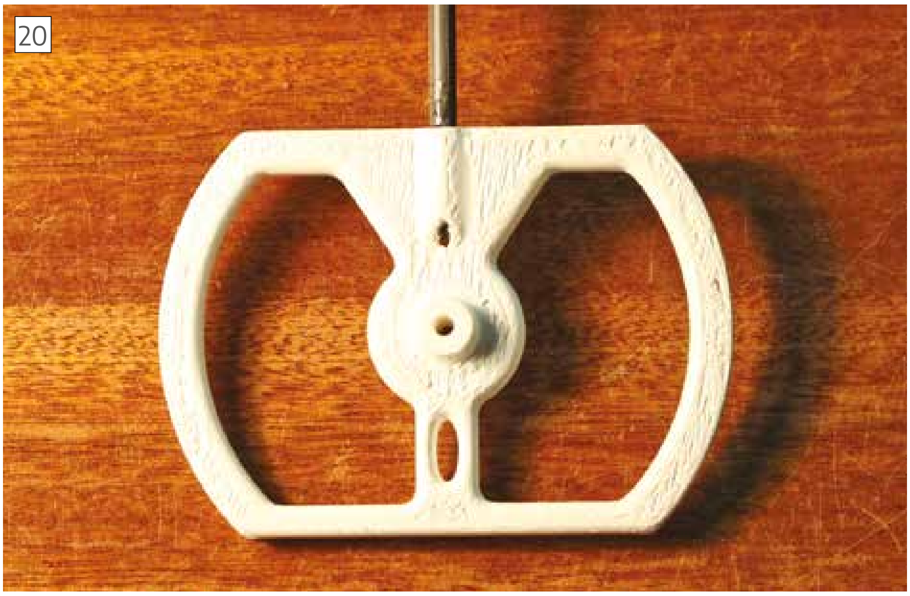
The new suspension is light, folds up easily, and the design includes adapters for attaching various modules such as cameras, panning motors, altimeters and GPS sensors. The upper TriTaper jamming socket is inspired by the familiar Morse Socket and usually carries an altimeter or roll stabiliser. Experiments found that a 4º taper in this printed socket produced enough grab while the triangular section prevents rotation. Gadgets printed with TriTaper adapters can be stacked, adding multiple functions to an aerial mission. The 60cm long carbon beam attaches to the line by 3D printed Capstan Wraps with teeth that prevent slippage.

Creating the suspension pulleys encountered an issue with FFD printing where a good surface finish is hard to achieve on the underside of steep overhangs as seen in **photo 20**. This is because the required support leaves ragged scars along the points of attachment with filament droops between them. The problem is lessened as the support density increases but at the expense of more scarring and increased difficulty in removing that support.

●To be continued

New type of Aeronaut suspension made of 3D printed parts and carbon fibre tube. The altimeter is fitted into the TriTaper socket at top, while the PanGimal unit and camera is attached at the bottom.

Sequence of images showing how the geometry of the aeronaut suspension maintains the camera (to be attached at the bottom) at a constant angle relative to the kite line.



An attempt at printing one of the suspension pulleys as a single supported part resulted in a poor surface on the underside, even after painting.