TITLE: A Study of Bicycle Frame Customization Through the Use of Additive Manufacturing Technology

AUTHOR: James I. Novak

Part 1: Background

1.1 Definitions

This paper reflects upon the development of a 3D printed bicycle frame developed as part of the authors' university Honours project. For clarity it is important to delineate that the term *additive manufacturing technology* can be used interchangeably with the more mainstream term *3D printing*,[1] and has been globally standardised within ASTM F2792-12a. [2] With additive manufacturing technology advancing "faster than the speed of light",[3] research into the bike frame focuses on *future* developments within additive manufacturing so as not to create something that becomes outdated before completion. Specifically, analysis revolves around materials, printing technology, software and other factors predicted during the next five to ten years, the time many expect 3D printing to reach mainstream popularity.[4]

1.2 Customisation

Simultaneous practical investigations by Empire Cycles and Flying Machine into the creation of customisable bicycle frames using current 3D printing technology have been influential on this project. It is important to acknowledge that customisation is not a new concept to the world of bicycle design. Within this context customisation refers to the adjustment of a bicycle's geometry to fit the anthropometry of the rider, most often in relation to the three contact points between rider and bicycle: hands, feet and seat. Such customisation is nothing new and can be seen even in early nineteenth century velocipede designs where threaded rods were used to adjust the seat height and angle. The necessity for such adjustment relates to the stresses placed on the human body whilst riding, with a good fit ensuring a long-term safe and enjoyable experience,[5] while for athletes the primary driver is to ensure they "perform closer to their absolute physical peak". [6] Through additive manufacturing customisation is no longer a process that occurs after manufacture, but can be integrated early in the digital design stage without negatively affecting manufacturing times or cost between iterations.

Empire Cycles are an established low-volume manufacturer of mountain bikes based in the United Kingdom, winning the coveted Red Dot Design Award in 2010 for their premium AP-1 downhill mountain bike (manufactured traditionally). Known for innovation, their latest project in partnership with 3D printing company Renishaw is the first mountain bike frame to be manufactured using only additive processes (figure 1) with customisation opportunities one of the key drivers.[7] Fine-tuning of the frame's geometry takes place inside 3D CAD software, meaning that variations inherent between individuals can be measured and accommodated at the design stage, before the perfect one-off titanium frame is printed for that individual. In order to meet the size limitations of current metal 3D printers, the frame is divided into smaller sections shown in figure 2, and assembled later.

Figure 1 Empire Cycles, 3D printed bicycle frame 2014, 3D printed titanium frame with standard bicycle components attached.

Figure 2 Empire Cycles, 3D printed bike frame sections 2014, 3D printed titanium using an AM250 Laser Melting Machine, 300 x 250 x 250cm.

Similarly Flying Machine, a younger Australian company, has taken advantage of the customisation benefits of additive manufacturing in partnership with the CSIRO. Their commercialised bicycle frames such as the ‘F-ONE-HD’ (figure 3) require customers to go through a fitting process prior to the design being adjusted in CAD, and finally printed in Titanium. In contrast to Empire Cycles however, the only components 3D printed and modified are the lugs (figure 4), which are then joined to standard extruded tubes of titanium, combining new technology with this traditional method of manufacture.

Figure 3 Flying Machine *F-ONE-HD* 2014, Frame constructed from 3D printed titanium lugs and extruded titanium tube with standard bicycle components attached.

Figure 4 Flying Machine, 3D printed lugs 2014, 3D printed titanium.

Both cases present a radical shift from the traditional model of mass-production where frames are either offered as one-size-fits-all (as in the AP-1), or in a selection of small, medium and large sizes. Such sizing schemes require a ‘close-enough is good enough’ mentality, with fine-tuning for the customer accommodated through adjustable components at the contact points with the rider. Significantly, despite ideals of perfect user fit, figure 5 and figure 6 show that traditional adjustment for the saddle has still been provided in both designs. This led to the question; were these companies were really taking full advantage of the ability of 3D printing to create one-off customised products, or were they dealing with genuine limitations of the current additive manufacturing process? It also revealed the potential for 3D printing to be used as a marketing tool to increase sales and offer a point-of-difference within a competitive market.

Figure 5 Empire Cycles, Seat adjustment detail 2014, 3D printed titanium frame with traditional seat post.

Figure 6 Flying Machine, Seat adjustment detail 2014, 3D printed titanium lug with traditional seat post.

Through the design of a new bicycle frame it became important to explore this tension, focusing particularly on the saddle and the ability to adjust its’ position within Solidworks CAD software as a part of the frame, rather than an accessory. Using the authors’ own anthropometric measurements for the final model, the bulky adjustable components evident in a traditional bike have been eliminated (figure 7), resulting in a frame where the saddle attachment is printed in the optimal position for the authors’ own body proportions as a truly one-off piece. This proves that it is possible to print a bicycle frame that meets the specific anthropometry of an individual without the need to include traditional adjustable components. However fore and aft adjustment of the saddle remains in this design in order to accommodate the fitting of a standard bicycle saddle, although could receive the same level of personalisation using a different type of saddle and fixing the perfect position within the digital model. As a final detail, ownership of the bike has been signified by including the authors last name into the frame design (figure 8), a feature that can be modified for any customer in a way that only 3D printing could achieve.

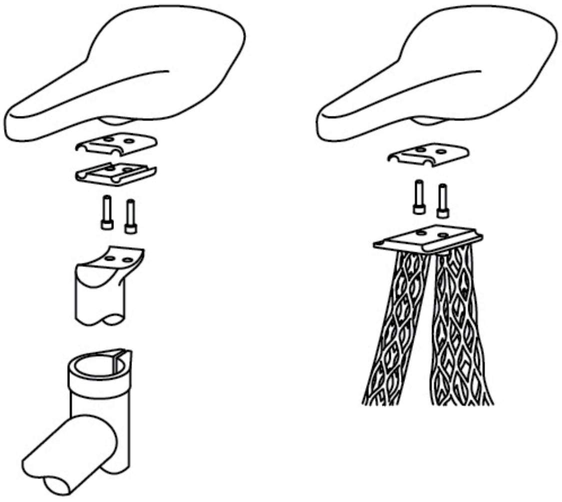

Figure 7 James Novak, Reduction of components between the original bicycle (left) and the 3D printed version (right) 2014, illustration.

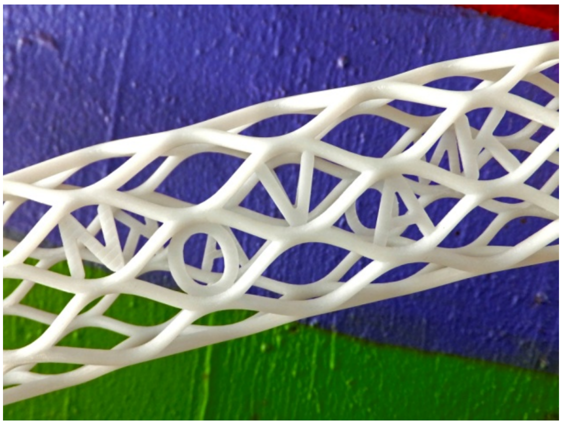

Figure 8 James Novak, Name embedded in 3D printed frame 2014, Stereolithography (SLA).

1.3 Data-Driven Design

Interwoven with customisation in the exemplars from Empire Cycles and Flying Machine is the use of data collected about the user to determine the geometry of the final frame. Rather than designers creating each new model from the ground up, selected dimensions are adjusted within CAD, which in this project is achieved by modifying a single dimension in Solidworks that controls the seat height (figure 9). The software then rebuilds the frame automatically using the new data due to its parametric capabilities. This is where CAD software like Solidworks creates relationships between parts or features, meaning that if one is changed, others may automatically update within given parameters. This differs over traditional modelling programs where if something changes, elements must be manually re-modelled to accommodate, requiring more time and diligence on the part of the designer. Empire Cycles have furthered this automated process through the use of Topological Optimisation[8] software, allowing the computer to calculate where material is required in the most efficient strength-to-weight ratio given a set of known maximum forces, essentially designing the final product autonomously.

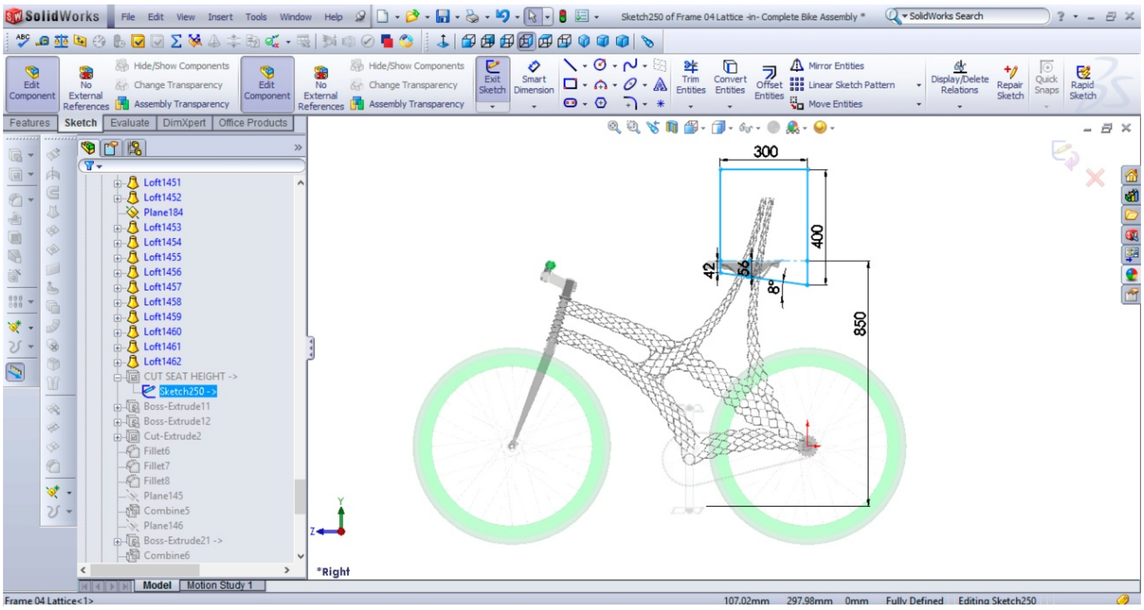

Figure 9 James Novak, Modifying the 850mm dimension generates a new frame 2014, screen capture.

Focusing on the seat post area of the Empire Cycles design, the original aluminium alloy version designed by humans and manufactured through traditional casting techniques weighs 360g, while the version calculated and designed automatically by the computer before being 3D printed in titanium only weighs 200g. This is the power of the data-driven future described by authors like Campbell, Bourell and Gibson,[9] indicating the changing role of the designer and associated 3D design software. Unfortunately the tools have proven prohibitively expensive for a student to access, with proprietary software like ‘Within Enhance’ quoted to the designer at £30,000. This highlights a gap that currently exists between available CAD software and the tools required to truly take advantage of 3D printing capabilities. Within Solidworks however, elements of autonomous generation have been achieved through the use of guides (figure 10) and 2D sketches, which the software has then used to generate 3D geometry in the way it calculates to be most efficient between these 2D planes (figure 11). Although lacking the crucial link to strength and requiring a significant level of manual input, the future will certainly see more appropriate, cost-effective tools become available as demand grows in parallel to 3D printing. Standard finite element analysis (FEA) tools within Solidworks have proven incapable of processing the complexity of the resulting bicycle frame design, causing the software to crash when challenged to assess even a small segment of the frame under load. Again this points to the challenges designers face in adopting additive manufacturing using current technologies, with companies like Empire Cycles and Flying Machine requiring partnerships with large research companies in order to access high-end computing software and hardware.

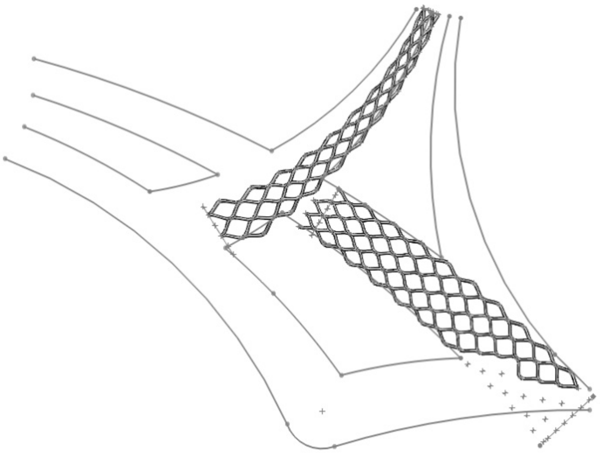

Figure 10 James Novak, Solidworks guide sketches 2014, Solidworks screen capture.

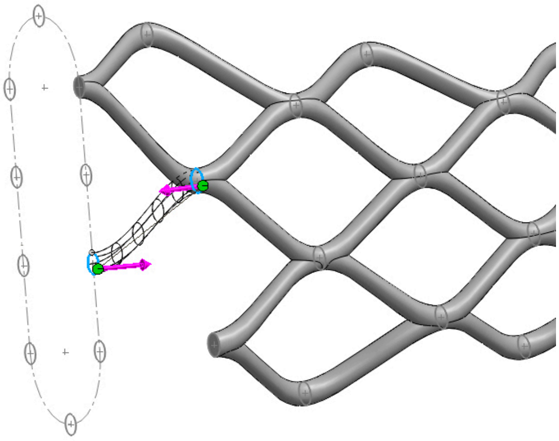

Figure 11 James Novak, Automated 3D form generation between 2D sketches 2014, Solidworks screen capture.

1.4 Complexity

While adopting additive manufacturing technology provides numerous benefits, the third crucial driver that follows on from an automated computer process is the inherent ability to create complex geometry. Prior to additive manufacturing, the outcomes of Topological Optimisation tools had limited use as the forms determined by the computer were too complex for traditional moulding or subtractive processes to produce. However complex geometries can be readily produced in an additive process, resulting in the original Empire Cycles Aluminium frame weight of 2100g dropping by 33% to 1400g using 3D printed titanium[10] and computer optimised geometries. This is substantial in the cycling world where fractions of a second can separate athletes, with weight a direct contributing factor to speed.

Arguably the 3D printed components of Flying Machine's 'F-ONE-HD' have not embraced this third opportunity, with the lugs shown previously in figure 4 manufacturable through processes like casting, CNC machining or even metal injection moulding. The authors' need to investigate complexity has instead led further afield, finding mathematics and the work of Henry Segerman to challenge the notions of structure and three-dimensional form. His 3D printed works are created using mathematical formulae and computer coding to determine their form, in a similar fashion to the automated process of Topological Optimisation. The resulting objects exhibit "intricate internal structures [that] can be very difficult to produce"[11] outside of 3D printing, a benchmark to which the bicycle frame of this project must reach in order to successfully fulfil all criteria of additive manufacturing.

At this early stage of additive manufacturing the bicycle frames from Empire Cycles and Flying Machine certainly engage with the technology, yet scope for improvement is evidenced around the key areas of customisation, data-driven design and complexity. Both projects are in their infancy and exploit the technologies available today; however with additive manufacturing exponentially growing in line with Moore's Law,[12] designing for what can be achieved today leaves room for others to push the boundaries and prepare for what will come tomorrow.

Part 2: Reinventing the Bicycle Frame

2.1 Experimentation

Returning to university after working as a professional Industrial Designer, a crucial step in this design project has been to transform the ingrained manufacturing 'rules' for traditional processes like injection moulding into an understanding of the new 'rules' when designing for 3D printing. Beginning with Solidworks, the same CAD software used in industry, it was discovered that complex forms controlled by strict dimensional constraints could be generated using identical tools to those implemented in the creation of manufacturable components. Completed files are exported in STL (Stereolithography) format, the native file read by all 3D printers, prior to being loaded into print software linked to a 3D printer. Only through physical experimentation could the link between theory and practice be realised.

Figure 12 demonstrates an early outcome where an 'Up! Plus 2' print failed due to an overly thin material section; by changing a single dimension in Solidworks, the parametric model automatically rebuilt and successfully printed less than three hours later. Figure 13 shows a later experiment where the same STL file was printed on the three different printers available in Griffith University's 3D printing lab, developing greater awareness of the differences in quality and materials of different machines, as well as quantitative data related to printing time, resolution and post-processing time. The post-processing relates specifically to the supporting elements added to a print for long overhanging sections of a model, preventing them from sagging and failing. Basic desktop printers like the 'Up! Plus 2,' one of the printers available at Griffith University, have only one print nozzle, so the support structure it creates is the same material as the model itself. Once complete, this must be manually trimmed away, and depending on the part complexity, can be a laborious process. Higher-end Fused-Deposition Modelling (FDM) printers can have two print nozzles, meaning that the support can be printed in a weaker material that dissolves or melts away later, requiring minimal hand clean-up. At Griffith, this includes the 'Fortus 250mc' which is also a FDM type printer, but includes a second print nozzle which prints a support structure that is soluble in a caustic soda solution; and the 'Projet HD 3500' which is a Multi-Jet Modelling technology using UV light to cure each layer, with a secondary nozzle printing wax as a support material, which is melted away in an oven at 70°C later. Selective Laser Sintering (SLS) printers require no support structure at all, with the bed of material supporting the print as it builds.

Figure 12 James Novak, Comparison of 3D printed lattice with different wall sections 2014, ABS plastic printed on an 'Up! Plus 2' FDM printer.

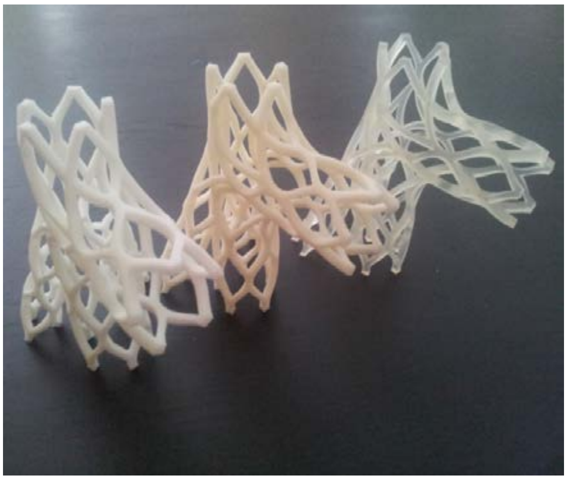

Figure 13 James Novak, Comparison of the same file printed on three different university printers 2014, left is ABS plastic from the 'Up! Plus 2,' middle is ABS plastic from the 'Fortus 250mc,' right is UV cured resin from the 'Projet HD 3500.'

Feeling the strength of these plastic parts raised questions about whether a lattice structure could compare to more solid forms, finding research by Park et al which identifies "the key characteristic of these structures is the high strength to weight ratios that can be achieved".[13] In line with the Topological Optimisation tools generating complex and strong organic forms for Empire Cycles, evidence suggests that structures seen in nature may be stronger and lighter than those typically made by man, and through additive manufacturing, are now possible to achieve. This evidence from both practical and theoretical research required a move towards physical testing to examine 3D printed structures and the inherent layer orientations generated through the process.

2.2 Testing

Pertinent to the research question is an awareness of current material properties and strength in order to understand what may improve during the coming years as technology advances. Tensile test pieces were printed on an ‘Up! Plus 2’ printer, designed in accordance with Australian Standard AS 1145.2-2001, and oriented in both vertical and horizontal configurations to compare the affect of layers under tensile loading. Along with prints on the ‘Fortus 250mc’ and ‘Projet HD 3500,’ outsourced prints using a Selective Laser Sintering (SLS) process from Shapeways, an online marketplace for 3D printing, were also purchased. The data collected from the ‘Up! Plus 2’ prints (figure 14) shows the significant difference in strength between the 2 orientations, while figure 15 shows a comparison of the vertical orientations across all four printers, which vary in both material and process.

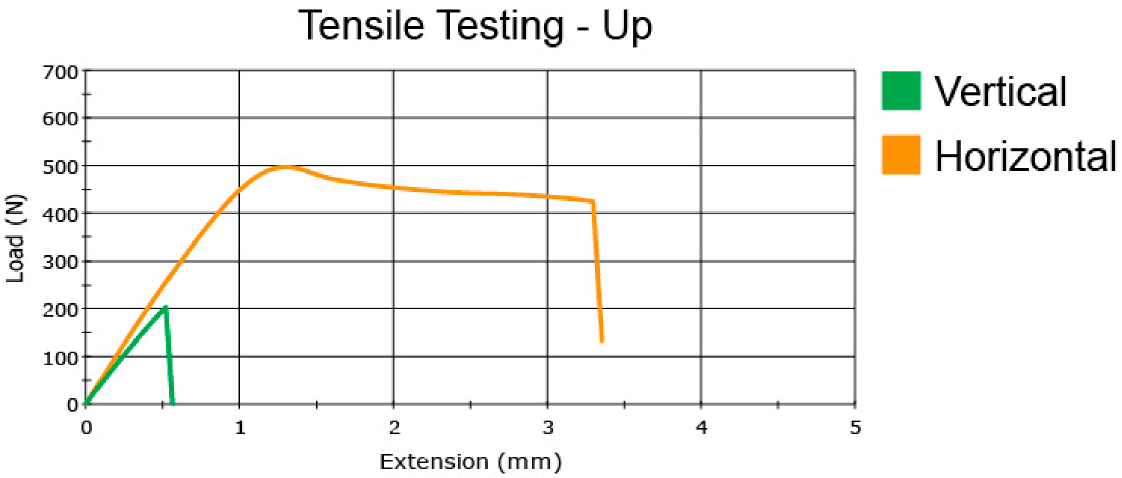

Figure 14 James Novak, Tensile test results (average) from the ‘Up! Plus 2’ printer 2014, graph.

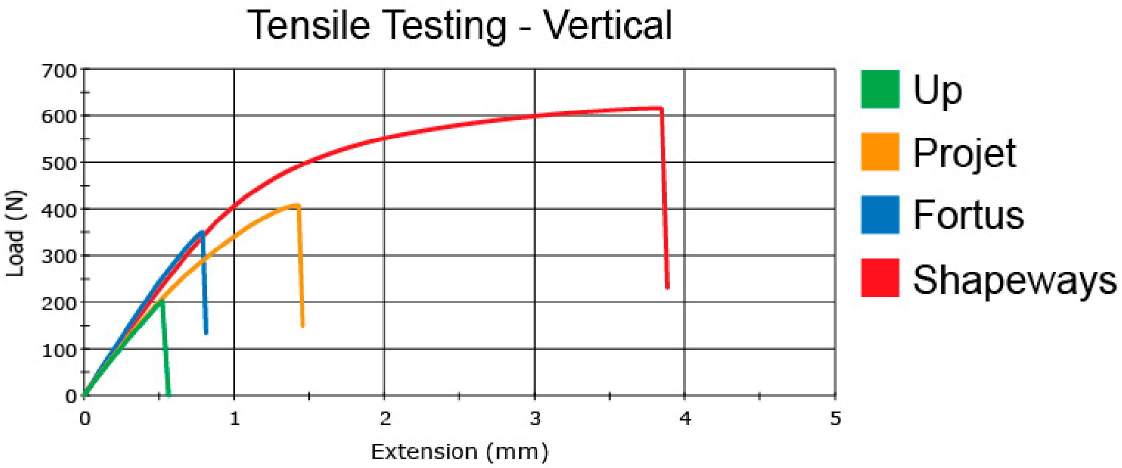

Figure 15 James Novak, Tensile test results between four printers 2014, graph.

Similar tests were performed for compressive forces, where not only was print orientation compared between four printers, but two different structures which utilise exactly the same amount of material as shown in figure 16. Although the data shown in figure 17 shows the tube to be a stronger form in both print orientations, observation of the testing process highlighted a unique property of the lattice structure; rather than catastrophic failure as seen in the tube designs (figure 18), the lattice would simply compress like a spring and return to nearly its' original shape once load was removed (figure 19).

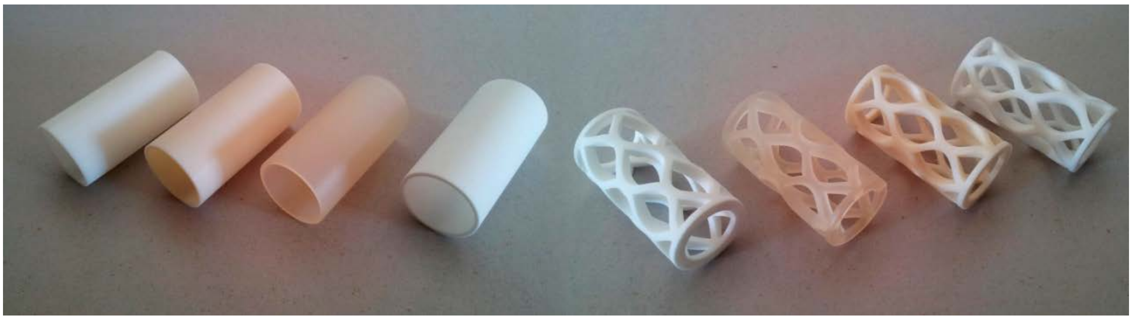

Figure 16 James Novak, Selection of compressive test pieces printed on four different printers 2014, variety of 3D printed plastics.

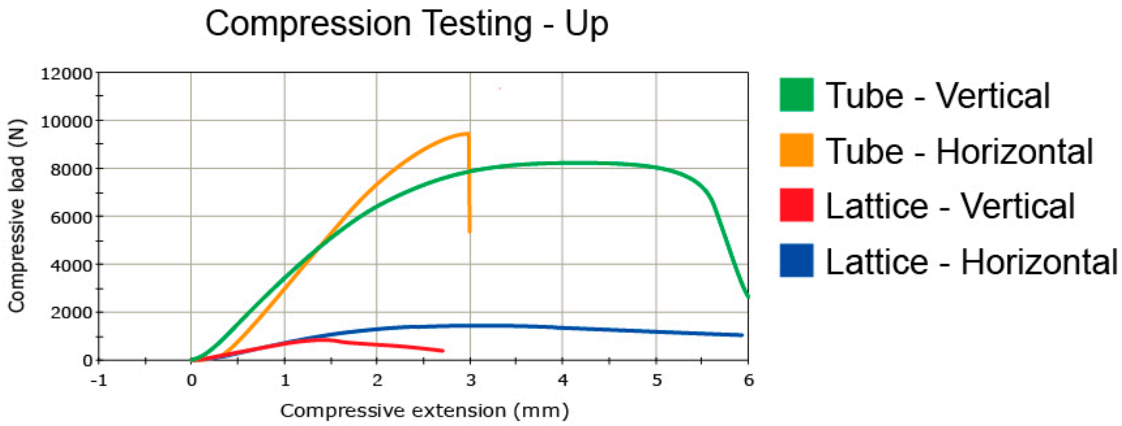

Figure 17 James Novak, Compressive test results (average) from the 'Up! Plus 2' printer 2014, graph.

Figure 18 James Novak, *Compression of a Tube – Horizontal* 2014, ABS plastic printed on an 'Up! Plus 2' printer.

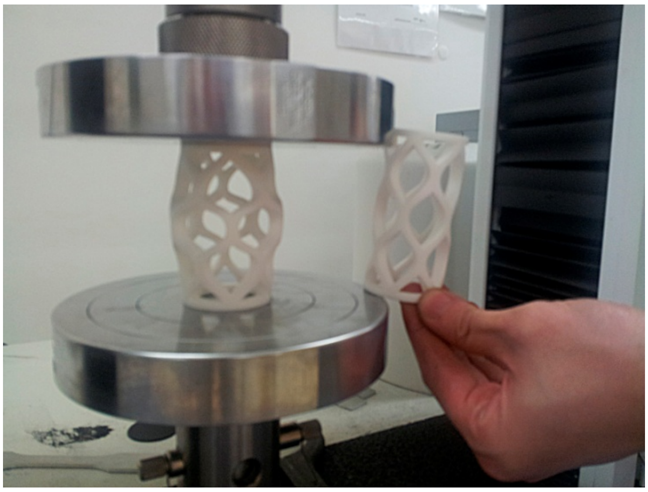

Figure 19 James Novak, Compression of a Lattice – Horizontal 2014, ABS plastic printed on an 'Up! Plus 2' printer.

Both tests provide significant insight into the technical attributes of a 3D printed component, informing the final design and subsequent prototype prints. While more extensive studies were desirable with a greater quantity of test pieces, the cost of materials and time to pursue this investigation within a short Honours program prevented further destructive testing. However this is the first time such complete data has been collected about the Griffith university printers, and is worth pursuing at another time through a more comprehensive study. Many 3D printed materials provide specifications about maximum stresses and loadings; however only through practice-led research can the application of these be fully understood. This is particularly evident when considering the layer-orientations generated through the process, which are inherently stronger in one direction over another; a factor not seen in any other manufacturing process.

2.3 Frame Creation

Concurrently the design of the fixed-gear bicycle frame has evolved out of these experiments into CAD software, 3D printing capabilities and materials. An early completed model emerged after research into three-dimensional tessellation and crystalline micro-structures, with ensuing test prints of a truncated octahedron structure (figure 20) proving both strong and capable of printing without any support structure. However the geometric repetition of the design failed to significantly push the boundaries of complexity identified through research into practitioners like Henry Segerman. Returning to the organic lattice structures created during experimentation (previous figure 13), the challenge became expanding this to a full-size frame that must be intricate and organic, yet structured and dimensionally accurate to allow for assembly into a working bicycle.

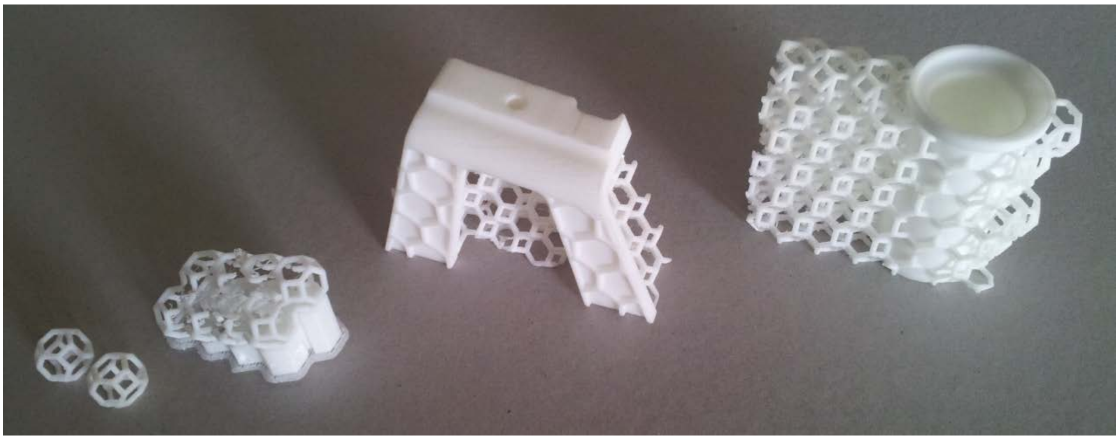

Figure 20 James Novak, Test prints of truncated octahedron structures 2014, ABS plastic printed on an 'Up! Plus 2' printer.

After enrolling into a training course for another CAD program called Rhinoceros, or Rhino3D, which has the capacity to use mathematical algorithms to generate three-dimensional models, the time required to learn the advanced skills necessary to generate complex structures yet retain geometric control indicated that time would be better spent challenging the parametric tools provided by Solidworks. 150 hours were spent creating the final CAD model of the frame, and brought about a new understanding of how to efficiently model a complex form with a final STL file size under 100MB, which is the maximum allowed by online printing bureau i.Materialise, while Shapeways is limited to only 64MB. One of the keys to meeting these file limitations was the discovery of merging solid geometry, as opposed to the original modelling method where segments of the frame were left as separate bodies that intersected. While both modelling methods produce the same visual outcome figure 21 shows a segment where geometry intersects, resulting in a file size of 11.6MB, while figure 22 is the same segment, only merged as a single solid and nearly half the file size at 6.1MB. For small test prints this difference had never caused a problem, but at the scale of a bicycle frame was a significant discovery to make the file printable. As designers move towards ever more complex forms, file size very quickly becomes a limitation that can only be met through clever CAD modelling decisions, or reducing the final resolution of the STL file. This is another example of the need to conduct research that is led by practice, informing the designer of the link between the theory and a practical awareness of what can be achieved within a file size of 100MB.

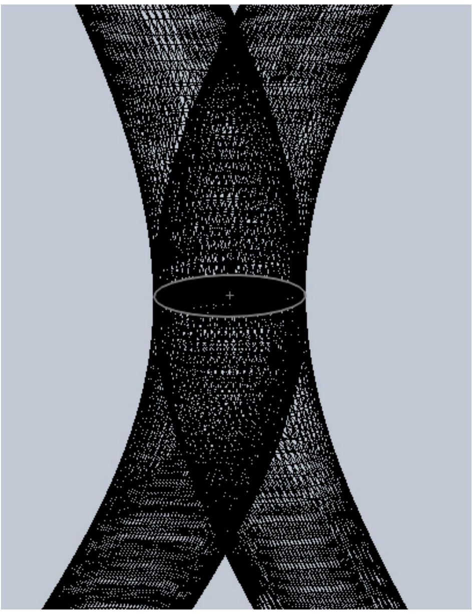

Figure 21 James Novak, Separate bodies intersecting with file size 11.6MB 2014, Solidworks screen capture.

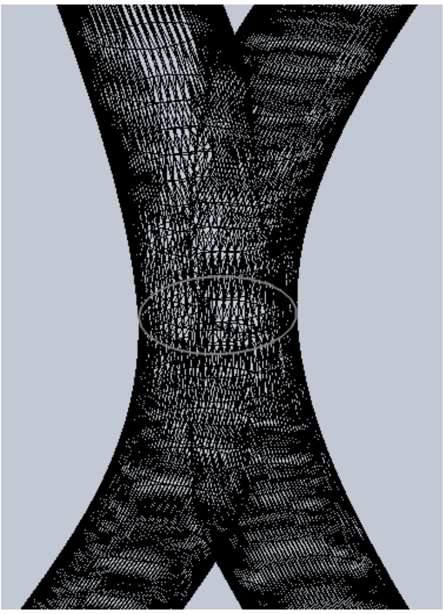

Figure 22 James Novak, Merged bodies with file size 6.1MB 2014, Solidworks screen capture.

2.4 Frame Printing

While the frame looks towards future developments of 3D printing technology, where printing sizes and speeds will inevitably increase and a greater variety of materials will be available, it became important to compare the media hype surrounding current 3D printing with the reality of what can actually be achieved today. The difficulty came in finding a printer large enough to accommodate the frame; despite working with supervisor Dr Jennifer Loy to contact a variety of companies and research institutions around the world, only i.Materialise agreed to print the frame using Stereolithography technology (SLA). This is the oldest form of 3D printing, and as such has had time to mature with a print volume up to 2100 x 700 x 800mm. The trade-off is that the material is a fragile resin, which became evident over the hot Australian summer where the bicycle, despite being stored in-doors and away from sunlight, melted and distorted beyond use.

This emphasises the material and technological limitations currently restricting designers, with rules and limitations just like any other manufacturing method. Beyond the prototype, the bicycle frame is certainly a design positioned to take advantage of the burgeoning 3D printing technology over the next decade, with numerous avenues to continue testing in preparation for the day the frame can finally be manufactured through additive means. Following the example of both Empire Cycles and Flying Machine who collaborate with 3D printing companies, the opportunity to build upon the relationship with Materialise over the coming years may result in a final marketable product that transforms bicycle manufacturing. Composite materials such as continuous carbon fibre and Kevlar are now surfacing through companies like MarkForged, and will likely result in new opportunities to realise a functional, customisable bicycle frame unlike anything seen before.

Part 3: Conclusion and Future Directions

The primary concern of this research has been to generate new knowledge and awareness of additive manufacturing through the practice of 3D printing a bicycle frame. This practice-led inquiry has addressed the core attributes acknowledged by leading theoreticians, focusing particularly on the key areas of customisation, data-driven design and complexity. The opportunities these features provide signal a move away from mass production towards a likely third industrial revolution, driven by consumer desires for personalised products that meet their unique requirements. Within the world of cycling this may either reflect a level of individuality, or provide an athlete with a competitive advantage. Both Empire Cycles and Flying Machine are engaging with these issues within the limits of what is currently possible, yet with the rapid advancement of 3D printing technologies, the risk of designing for today is that the outcome is obsolete by tomorrow.

The bicycle frame created during this project has evolved through the exploration of tensions between materials, processes and software available now, and those predicted during the next five to ten years. The outcome proves it is possible to customise a design using data; however current high-end CAD tools like Solidworks or Rhinoceros require advanced skills to begin applying even basic control over a design, certainly beyond the capabilities of a consumer. Similarly the borrowing of complex structures seen in nature can theoretically result in stronger and lighter objects, yet testing of these requires expensive computer software and investment in a significant quantity of printed pieces for destructive testing. In order to keep up with the demands of designers, tools necessary to both design and test the new forms possible through additive manufacturing technology need to become integrated into CAD software, growing in conjunction with 3D printing. Ultimately it has been shown that additive manufacturing technology significantly enhances the ability to customise a bicycle frame to suit an individual riders’ anthropometry.

References

---

[1] Robert Grace, "Wohlers Report Says 3-D Printing Exploding" (2013/06/24/ 2013).

[2] ASTM, "F2792 - 12a: Standard Terminology for Additive Manufacturing Technologies," (West Conshohocken: ASTM International, 2012).

[3] Hod Lipson and Melba Kurman, Fabricated : The New World of 3d Printing, (Somerset, NJ, USA: Wiley, 2013), http://site.ebrary.com/lib/griffith/docDetail.action?docID=10657814.

[4] Publications describing the adoption of 3D printing to be five to ten years away include Michael Molitch-Hou, "Consumer 3d Printing More Than 5 Years Away from Mainstream Adoption, Says Gartner," 3D Printing Industry, http://3dprintingindustry.com/2014/08/20/consumer-3d-printing-5-years-away-mainstream-adoption-says-gartner/; Bob Vavra, "Additive Manufacturing Is Shaping the Future," *Plant Engineering* (2013).

[5] Anonymous, "Individualized Bicycle Design," *Journal of Physical Education, Recreation & Dance* 71, no. 5 (2000).

[6] Ben Delaney, "Dr. Andy Pruitt: Cycling's Biomechanical Guru," *Bicycle Retailer and Industry News* 10, no. 8 (2001): 20.

[7] Renishaw, "First Metal 3d Printed Bicycle Frame Manufactured by Renishaw for Empire Cycles," Renishaw, http://www.renishaw.com/en/first-metal-3d-printed-bicycle-frame-manufactured-by-renishaw-for-empire-cycles--24154.

[8] Topological Optimisation utilises mathematics and computer simulation to automatically calculate “the ‘logical place’ for material – normally using iterative steps and finite element analysis.” (refer to ibid.2.)

[9] Ian Campbell, David Bourell, and Ian Gibson, "Additive Manufacturing: Rapid Prototyping Comes of Age," *Rapid Prototyping Journal* 18, no. 4 (2012): 258.

[10] Renishaw, "First Metal 3d Printed Bicycle Frame Manufactured by Renishaw for Empire Cycles".

[11] Henry Segerman, "3d Printing for Mathematical Visualisation," *The Mathematical Intelligencer* 34, no. 4 (2012): 56.

[12] For example see Brian Krassenstein, "The Moore’s Law of 3d Printing… Yes It Does Exist, and Could Have Staggering Implications," 3dprint.com, http://3dprint.com/7543/3d-printing-moores-law/; Canalys, "3d Printing Market to Grow to Us$16.2 Billion in 2018," Canalys, http://www.canalys.com/newsroom/3d-printing-market-grow-us162-billion-2018; Davide Sher, "3d Printing Industry to Grow by 400% over the Next 4 Years, According to Wohlers," 3DPrintingIndustry.com, http://3dprintingindustry.com/2014/09/02/3d-printing-industry-grow-400-next-4-years-according-wohlers/.

[13] Sang-In Park et al., "Effective Mechanical Properties of Lattice Material Fabricated by Material Extrusion Additive Manufacturing," *Additive Manufacturing*, no. 0.

Image Reference List

Figure 1. Renishaw. "First Metal 3d Printed Bicycle Frame Manufactured by Renishaw for Empire Cycles." Renishaw, http://www.renishaw.com/en/first-metal-3d-printed-bicycle-frame-manufactured-by-renishaw-for-empire-cycles--24154. 4.

Figure 2. Renishaw. "First Metal 3d Printed Bicycle Frame Manufactured by Renishaw for Empire Cycles." Renishaw, http://www.renishaw.com/en/first-metal-3d-printed-bicycle-frame-manufactured-by-renishaw-for-empire-cycles--24154. 5.

Figure 3. Flying Machine. “F-ONE-HD, Luxury Single Speed.” Flying Machine. http://www.flyingmachine.com.au/2014/07/f-one-hd-luxury-single-speed-3d-printed-titanium/.

Figure 4. Hanlon, Mike. "Flying Machine Incorporates 3d Titanium Printing into US$3150 Bicycle Production Process." Gizmag, http://www.gizmag.com/3d-printed-titanium-bicycle-frame-flying-machine/30875/.

Figure 5. Renishaw. "First Metal 3d Printed Bicycle Frame Manufactured by Renishaw for Empire Cycles." Renishaw, http://www.renishaw.com/en/first-metal-3d-printed-bicycle-frame-manufactured-by-renishaw-for-empire-cycles--24154. 4.

Figure 6. Flying Machine. “F-ONE-HD, Luxury Single Speed.” Flying Machine. http://www.flyingmachine.com.au/2014/07/f-one-hd-luxury-single-speed-3d-printed-titanium/.

Figure 7. Novak, James. “Reduction of components between the original bicycle and the 3D printed version.” 2014

Figure 8. Novak, James. “Name embedded in 3D printed frame.” 2014

Figure 9. Novak, James. “Modifying the 850mm dimension generates a new frame.” 2014

Figure 10. Novak, James. “Solidworks guide sketches.” 2014

Figure 11. Novak, James. “Automated form generation between 2D sketches.” 2014

Figure 12. Novak, James. “Comparison of 3D printed lattice with different wall sections.” 2014

Figure 13. Novak, James. “Comparison of the same file printed on three different university printers.” 2014

Figure 14. Novak, James. “Tensile test results (average) from the ‘Up! Plus 2’ printer.” 2014

Figure 15. Novak, James. “Tensile test results between four printers.” 2014

Figure 16. Novak, James. “Selection of compressive test pieces printed on four different printers.” 2014

Figure 17. Novak, James. “Compressive test results (average) from the ‘Up! Plus 2’ printer.” 2014

Figure 18. Novak, James. “Compression of a tube – horizontal.” 2014

Figure 19. Novak, James. “Compression of a lattice – horizontal.” 2014

Figure 20. Novak, James. “Test prints of truncated octahedron structures.” 2014

Figure 21. Novak, James. “Separate bodies intersecting with file size 11.6MB.” 2014

Figure 22. Novak, James. “Merged bodies with file size 6.1MB.” 2014