Rapid Manufactured Textiles

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Abstract

Rapid Manufacturing (RM) is increasingly becoming a viable manufacturing process due to dramatic advantages that are achievable in the area of design complexity. Through the exploration of the design freedom, this paper introduces the concept of manufacturing textiles for potential smart and high performance textile applications. This paper discusses the current limitations associated with the manufacture of textiles through RM and presents a novel methodology for the generation of 3D conformal RM textile articles. The paper concludes that through RM it is entirely possible to manufacture a structure that incorporates drape and free movement properties directly comparable to conventional textiles.

Introduction

This paper describes the new application of manufacturing textiles through future Rapid Manufacturing (RM) technologies. As this is an entirely new application for RM, the authors intend that this paper be viewed as a precursor to further research that is needed to fully explore the potential of Rapid Manufactured textiles. All of the findings discussed are the subject of current research being undertaken by the authors [1,2].

RM has become a generic term used for a classification of technologies enabling the manufacture of end-use components without the application of conventional tooling [3]. Utilising additive layered manufacturing techniques similar to those developed in Rapid Prototyping (RP), components are manufactured directly from a three-dimensional (3D) Computer Aided Design (CAD) model [4].

Conventional manufacturing processes are generally subtractive or formative in nature, where the manufacturing element of the production process refers to the removal or moulding of material when creating a desired geometry. In contrast, RM technologies utilise additive manufacturing techniques. Here, discreet slices are taken from the 3D CAD geometry. The slices taken relate directly to the build layers of the RM process targeted for manufacture. The continual recreation of the discreet adjacent slices, layer by layer, via the RM system, allows the manufacture of virtually any complexity of geometry. The methods in which these layers are produced and the materials in which the components are built, vary significantly between the differing systems within the classification of the technology [5].

Scope of RM Textiles

When considering textiles and their applications many would only consider simple uses such as clothing and upholstery for furnishing, where in fact, the application of textiles is one of the most diverse globally. New technology in contemporary textile manufacture has served to narrow the gap between the worlds of art, design, engineering and science, enabling textiles to be utilised as an alternative material where flexibility would be advantageous. The inherent characteristics of textiles and their ability to provide form, function and aesthetics have led to applications ranging from the world of fashion to the world of architecture.

Increasingly, high performance and smart textiles are seen as relevant research areas [6,7], where the introduction of innovative technology in contemporary textiles and advances in material science have produced high performance specialised textiles capable of protecting against ballistic attack [Kevlar™], be self cleaning and antibacterial, control and transport moisture from the body [Gore-Tex™], provide thermal insulation and many other functions. The research surrounding high performance textiles relates to the materials that can be utilised in fibre production, the weave or structure of the resulting textiles and potential coatings and treatments to enhance functionality.

In contrast, smart textiles are derived from a concept first defined in 1990 concerning intelligent or smart materials [8,9]. Here the emphasis is not the measurable functionality or performance of the textile but the ability to sense stimuli from the environment and have the inherent capability to react and adapt to them by the integration of functionalities within the textile structure. Classification of smart textiles falls into three distinct categories: passive smart [10], active smart [11] and very smart [12], where each category provides a different level of intelligence. Almost all the current research concerning smart textiles is aimed at the creation of smart clothing [9,13,14,15,16], with the driving factor being society demanding the integration of intelligence into our local and daily environment. Clothing therefore provides the perfect vehicle for the integration of such intelligence, as it is an integral part of our personal environment, being adjacent to the body and worn almost anywhere and at anytime, offering a very unobtrusive and natural interface between humans and the potentially integrated desirable technology.

At the forefront of the smart clothing research is the creation of electrically conductive textiles or ‘electronic textiles’ where Electromagnetic Interference (EMI) shielding [17] and static dissipation are examples of commercially available products. Through the utilisation of such textiles that incorporate conductive fibres and the additional inclusion of standardised circuitry components, the vision becomes electronic clothing that integrates such items as the mobile phone and PDA, giving initial realisation to the goal of truly wearable computers and the first step towards truly smart clothing [9].

However, for smart and high performance clothing to become a manufacturing reality, especially for custom fitting items, several basic issues need addressing. The distinct unresolved issue that surrounds both smart and high performance textiles is their geometrical complexity and the subsequent need for a suitable manufacturing technique.

The current manufacture of the limited number of electronic smart garments requires a complicated manufacturing process chain starting with the manufacture of the textile itself. The structure of conventional manufactured textiles, be that high performance or smart, can be considered to be hierarchical, with the fibre (either staple: very short, or filament: longer) representing the smallest component within the hierarchy. The fibres are used to manufacture yarns or threads through processes such as spinning, and sequentially, threads are then used to manufacture textiles. The eventual textile manufacturing process relies on centuries old principles such as ‘weaving’ and, more recently, ‘knitting’. As with any other product, textiles have to be constructed with the manufacturing process in mind and therefore are fundamentally limited by the need to consider Design for Manufacture & Assembly (DFMA) criteria. If this point were extrapolated further to smart or high performance conformal textiles articles such as “cut and sewn” clothing constructed from flat sections of textiles, then the whole process would suffer from DFMA criteria twice, once during the manufacture of the textile itself, and secondly, through the manufacture of the garment from several flat textile sheets. Having created a garment the final stages would involve the integration of circuitry components providing the smart functionality to complete the garment.

Even considering this simplified manufacturing process chain, it becomes obvious why the number of electronic smart garments is limited and the actual result often cumbersome [9,15,16]. Given the design complexity advantages that are afforded by RM, this complicated manufacturing issue can be broadly solved if an additive manufacturing approach is taken. This elegant solution to the current paradigm of smart and high performance clothing indicates that the potential for RM textiles is considerable, albeit with significant research required.

Rapid Manufacturing

One of the main drivers for the creation of current and future RM systems and their respective build materials comes from the dramatic advantages that are possible in the area of design and geometry freedom [18,19]. The main benefit to be gained by utilising an additive manufacturing approach comes from the ability to produce parts of virtually any complexity, entirely without the need for tooling [18,20]. The absence of this tooling requirement when utilising additive manufacturing means that many of the restrictions of DFMA [21] that are essential in a modern manufacturing environment can be virtually eradicated [22]. Without the need for tooling or the necessity to consider any form of DFMA, the possibilities for design become limited only by the imagination.

This revolutionary aspect of RM means that geometry will no longer be a limiting factor in component design. Through RM, the possibility for highly complex, custom parts becomes apparent. The capability of RM to manufacture any complexity of design means that a new dimension of ‘Manufacture for Design’ rather the than the more conventional ‘Design for Manufacture’ philosophy [18] has been achieved. The elimination of tooling and the subsequent removal of many DFMA criteria realised through RM systems will promote significant benefits in the area of design. Cited benefits to product design include [3]:

- Design complexity / Optimisation
- Parts consolidation
- Body-fitting customisation
- Multiple assemblies manufactured as one

- Multiple free moving assemblies manufactured as one

While the subject of ‘Design for Rapid Manufacture’ [19] and its impact on product design is potentially broad, this paper focuses on the micro level or meso level design opportunities that are realised through RM and specifically, the potential to manufacture micro/meso level free moving assemblies in one manufacturing process, i.e. Rapid Manufactured textiles for smart and high performance applications.

Rapid Manufactured Textiles

The benefits of RM in the area of product design includes the ability to produce micro level or meso level free moving assemblies in one manufacturing process. Therefore, RM has the inherent capability to manufacture a type of structure or assembly that possesses drape and free movement; properties that are directly comparable to that of conventional fibre based textiles. When considering the structure of Maille (or chain-mail), utilised for armour before the 14th century [23], as demonstrated in Figure 1, then it becomes apparent that RM has the capability to additively manufacture an entire sheet of chain mail in one manufacturing process. This was first proposed by Evenhuis & Kyttanen in 1999 [24,25].

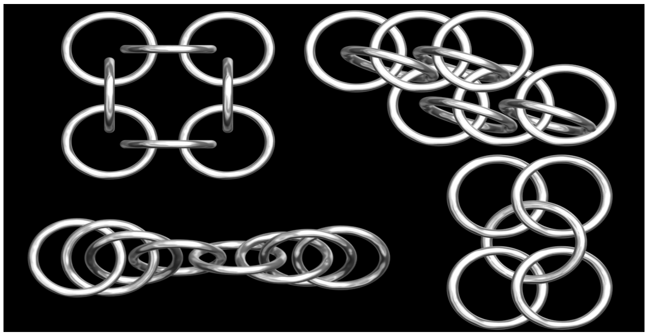

Figure 1: Historical examples of Maille or Chain-mail link configurations

The present requirement for RM textiles is to move away from the fundamental fibre type geometry as used in current manufactured textiles, demonstrated in Figure 2, to a fundamental link or linkable geometry, as demonstrated in Figure 3. The utilisation of such linkable geometry therefore provides the required free movement and drape characteristics inherent in conventional manufactured textiles.

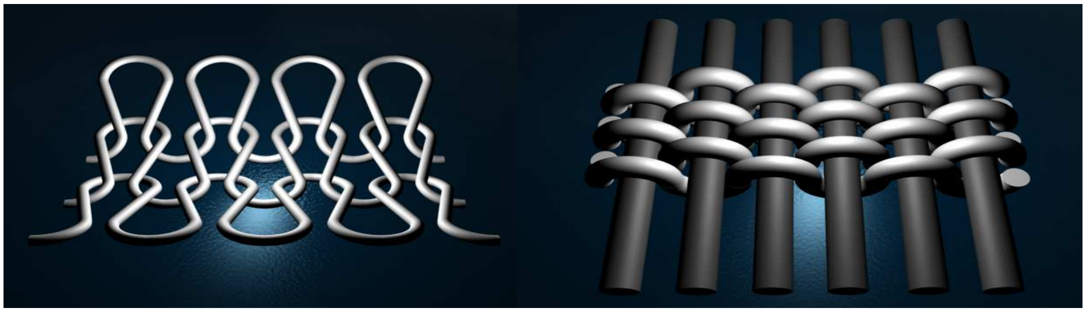

Figure 2: Conventional fibre based textiles, (left) knitted textile, (right) woven textile

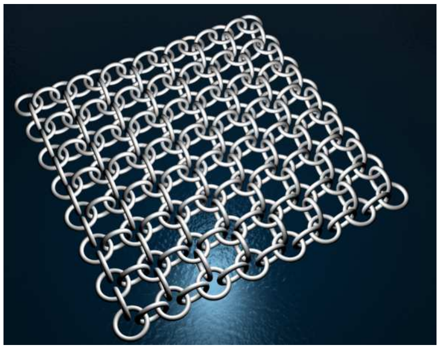

Figure 3: RM chain-mail textile

The potential of RM textiles is that DFMA criteria can be almost completely eradicated from the entire process. Firstly, the actual link or linkable geometry of the RM textile, due to the immense design freedom and manufacturing possibilities afforded by RM, could be any complexity of geometry. While the linkable geometry must have the inherent capability of interlinking with the adjacent structures and provide degrees of freedom for movement and drape characteristics, this is the only requirement placed upon it. Therefore the linkable geometry could be almost any smart or simple structure designed for a particular functionality.

While only a limited number of link designs have been considered so far, the potential exists to incorporate fully optimised smart structures, flexible linkages promoting elastic properties, hollow structures for thermal insulation, enclosed pockets for buoyancy and many other possible structures that could only be manufactured using additive techniques. Secondly, if one considers the manufacture of a RM garment, there would be no requirement to manufacture flat sheets of RM textile and then subsequently utilise those to produce a conformal garment. Within the design and CAD phase of the RM process, it would be possible to create a conformal seamless garment that required no DFMA criteria. Utilising this methodology it would be possible to create an entire garment, smart or otherwise in one manufacturing process, negating a large proportion of stages currently required within the conventional textile manufacturing sector.

Research Undertaken

The main requirement of RM is to have a robust 3D CAD model of the target geometry to be manufactured. This initial process when utilising additive manufacturing techniques represents the fundamental research issue which has prevented further advanced work being undertaken in the area of RM textiles. When manufacturing standardised macro level components via additive manufacturing, CAD representation is not a problematic issue. This is due to the shape and size of the target geometry and the design of the CAD systems which have been developed to support mainstream manufacturing techniques. When dealing with additive manufacturing techniques it is possible to manufacture any geometry that can be created within a CAD system. However, CAD has not been developed with the capabilities of additive manufacturing in mind and therefore it is possible to manufacture several geometries via additive manufacture that can not be represented in conventional CAD systems, for example Klein bottles and Steiner surfaces.

When creating 3D RM textile CAD data, it becomes necessary to model each individual link in the entire interlinking assembly. However, while the generation of simple link configurations and the subsequent generation of flat sheets of RM textiles, as demonstrated in Figure 3, within conventional CAD is not a difficult operation for experienced CAD users, problems do arise when considering conformal geometries. If a more complex geometry is considered, where the curvature of the final net shape of the RM textile article resides in all three axes, such as the hemisphere demonstrated in Figure 4, then current CAD systems are simply not capable of successfully or automatically mapping links over the surface in a uniform equidistant fashion so that the links tessellate successfully, also demonstrated in Figure 4.

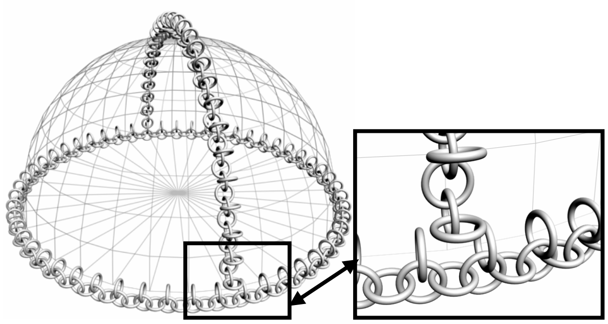

Figure 4: Hemispherical RM textile article, highlighting the inadequacies of conventional CAD

With sufficient time, expertise and the acceptance of extensive rework, it is possible to generate a complex 3D conformal textile in conventional CAD. This is demonstrated in Figure 5, which shows a CAD model and the subsequently produced world’s first 3D conformal seamless RM textile garment [26]. However, the CAD model for this article required two months to construct and utilised only a very simple linkable geometry, a torus. It can therefore be concluded that conventional CAD systems do not have the required capabilities for the generation of complex curved RM textile structures. Therefore there is a requirement to use an alternative to 3D CAD for the generation of 3D conformal RM textile data. The ability to create such curved RM textile structures represents a vital step in the generation of conformal RM smart and high performance textile articles and is the main aim of the ongoing RM textile research.

Figure 5: World's first 3D conformal RM textile garment, designed by Guy Bingham, CAD model (Left), actual garment (Centre & Right)

Textile CAD

Dedicated textile CAD packages do exist and have been investigated for their potential use for RM textiles [27,28,29]. A common feature of textile CAD packages is the concept of the Representative Volume Element (RVE). The RVE is the smallest possible repeating volumetric element and often the only part of the textile to be geometrically modelled. For reference, a representation of a basic chain-mail link and its associated RVE is shown in Figure 6 and Figure 7. Once the concept of using an RVE had been recognised, a methodology of lofting this over a conformal 3D surface was required. This approach was further investigated and a methodology was established for the generation of complex 3D conformal RM textile structures, as follows:

- 3D surface incorporating the final net shape of the desired RM textile created in CAD
- Finite Element (FE) mesh formed over the 3D surface
- RVE established within the textile CAD
- RVE mapped to the enclosed sections of the FE mesh
- Complete conformal RM textile data exported as STL
- STL uploaded to RM system for manufacture

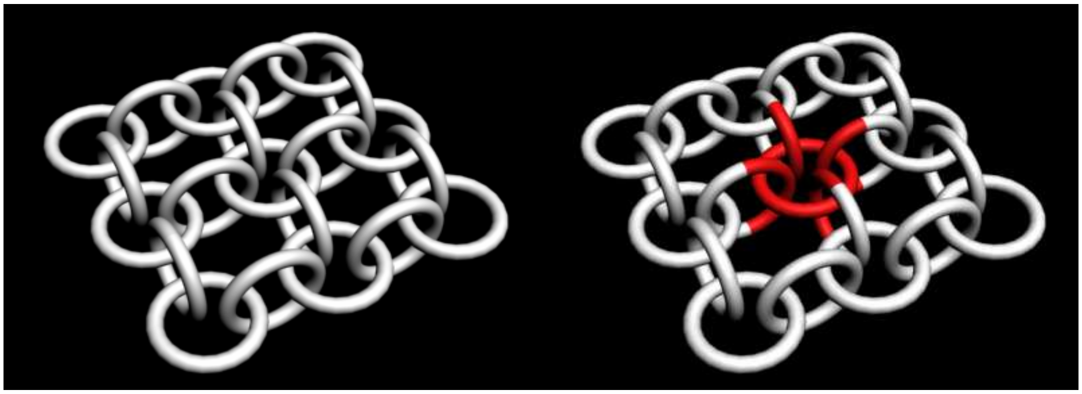

Figure 6: Basic RM chain-mail textile (Left) and the associated RVE (Right)

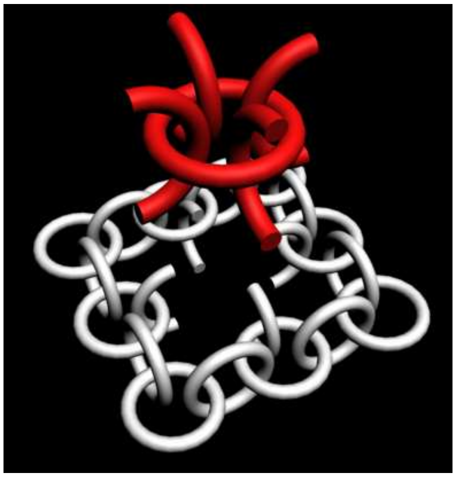

Figure 7: Exploded view of RVE

In order to fully expedite this work, collaboration was initiated with the Polymer Composites Research Group at Nottingham University to adapt some of their existing software, TexGen [30]. The TexGen software had been developed for the accurate and comprehensive FE modelling of the textile component of fibre reinforced composite structures [30]. The original purpose of the software was to generate Finite Element (FE) models for mechanical analysis of dry textiles and textile composites, as well as Computational Fluid Dynamics (CFD) to model infusion of textiles during composite manufacture.

The TexGen software relies on the generation of a suitable FE mesh. Utilising conventional stand alone FE software, a 3D surface of the required final net shape of the intended RM textile article can be imported and meshed. The newly created mesh can then be exported from the FEA software and imported into the TexGen system. Having already established the RVE of the particular RM textile link configuration to be utilised, the TexGen system then populates the RVE within the enclosed sections of the FEA mesh, matching the surface normal, rotation and scaling factor accordingly to create the final RM textile structure, demonstrated in Figure 8.

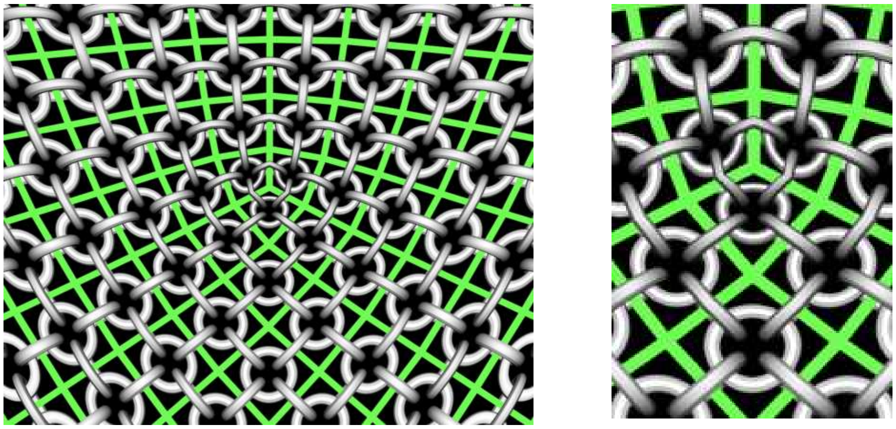

Figure 8: RVE mapped to enclosed sections of FE created mesh (green) (Left), close up (Right)

The results of the process can be seen successfully applied to the example of the hemisphere, as detailed in Figure 9.

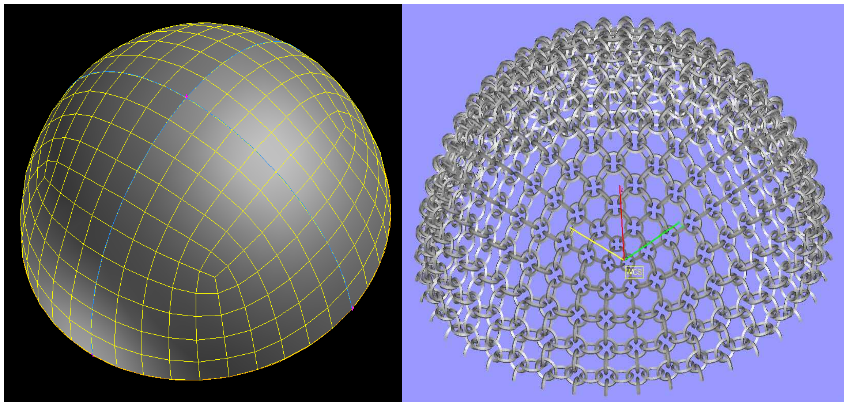

Figure 9: FEA mesh and TexGen created RM textile hemisphere

While the RM textile data produced using this system is not fully uniform, the system required no intervention and was fully automated once the FE mesh had been imported and the RVE fully established. The adaptation of the TexGen system thus offers a complete process for the generation of curved RM textile STL files and provides an important step forward.

The use of the adapted TexGen software and highlighted methodology is exceptionally fast compared to conventional CAD creating the RM textile hemisphere in Figure 9 within a two minute time frame. However, there are limitations. TexGen requires a vectorial description of the individual RM textile links for the RVE, from which smoothed paths are generated using simple parametric curves (e.g. Bezier curves) demonstrated in Figure 10.

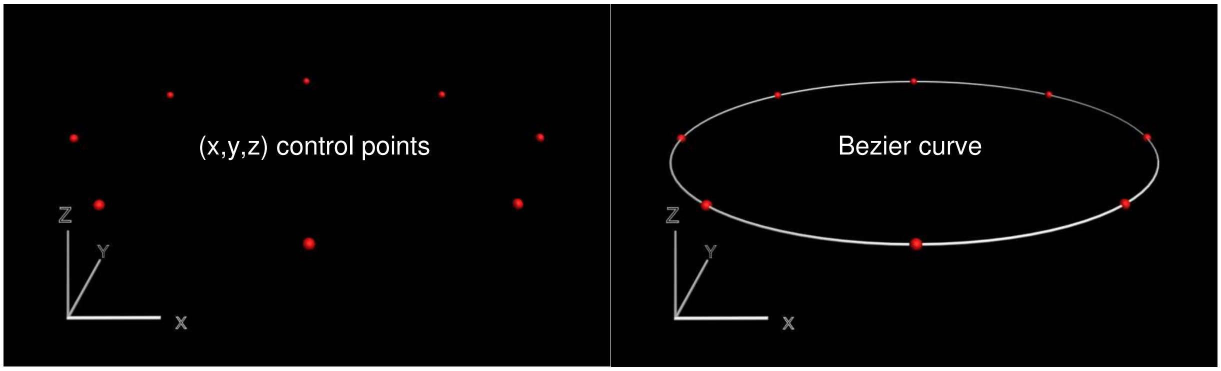

Figure 10: vectorial description of RVE, red control points in space (Left), Bezier curve (Right)

A 3D solid model is then generated by sweeping an assumed cross section along these paths creating the individual RM textile links, demonstrated in Figure 11.

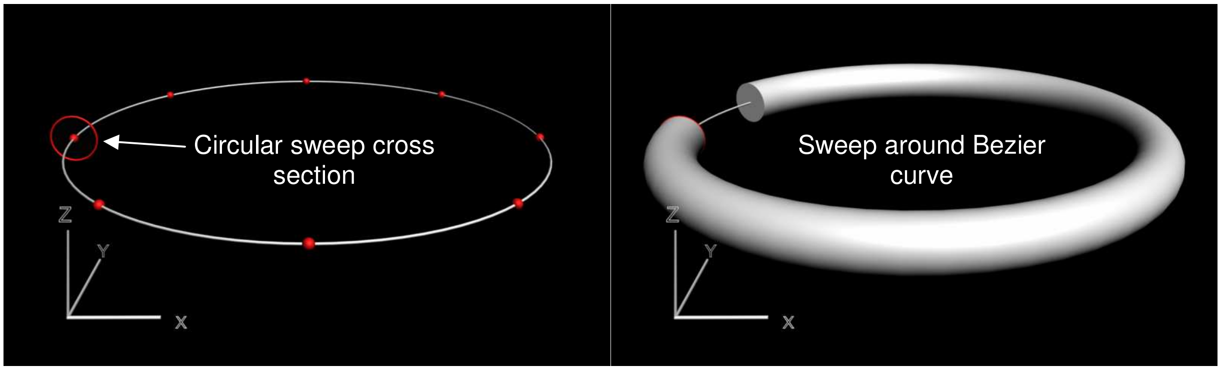

Figure 11: Circular cross section for Bezier curve sweep (Left), actual sweep (Right)

This system is therefore severely restrictive when more complex geometric shapes are considered and thus the system at present is limited to simple chain-mail type structures that can be easily defined using vectors.

Additionally, the meshes that are created within conventional FE software are not uniform in their structure and therefore distortion and deformation of the link structure occurs when populating the RVE. The type of mesh structure available for use by TexGen is also limited to quadrilaterals. This is demonstrated in Figure 12, which shows a 3D conformal surface that has been meshed using conventional FE software and shows the mesh populated with a basic chain-mail link RVE. The resulting deformation and inconsistency of the RM textile link structures would therefore adversely affect the resultant RM textile article's performance and could additionally affect the possibility of actual manufacture, as demonstrated in Figure 13.

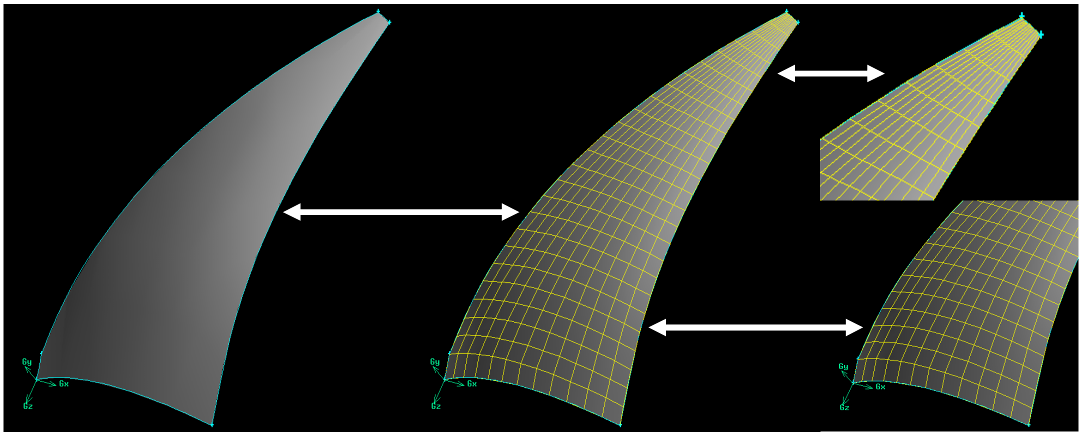

Figure 12: Non-uniform FEA meshing of conformal surfaces

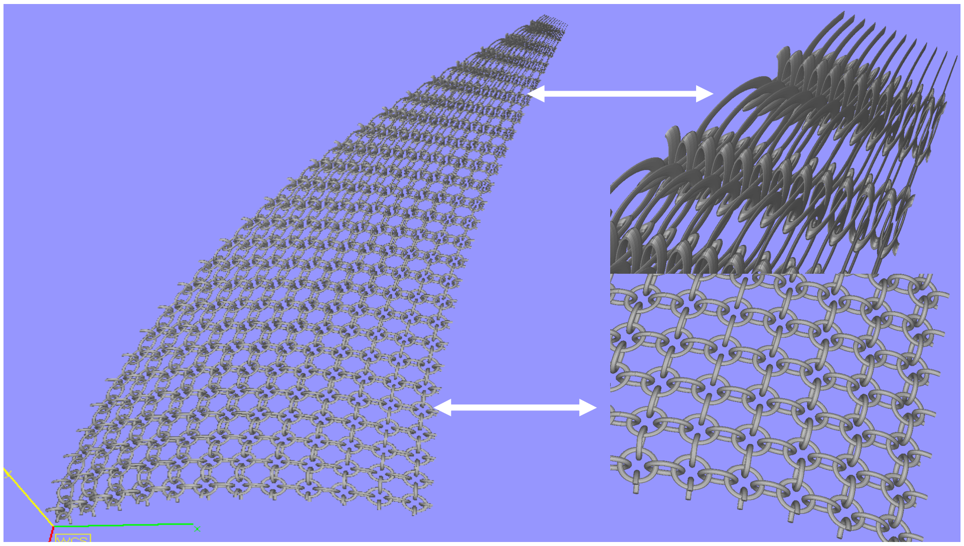

Figure 13: RVE populated FEA mesh, highlighting deformation of link structure

ChainLink Development

To address the limitations of the adapted TexGen RM textile methodology, research in collaboration with the Polymer Composites Research Group at Nottingham University was further initiated to produce a specific RM textile CAD tool, ChainLink [1,2]. The main premise of the software development was the capability of mapping any complexity of RM textile RVE structures. Utilising a similar FE mesh dependent methodology as the previous TexGen system, the main development was centred on the direct import of RM textile RVE CAD data, which therefore negates the previously required restrictive vectorial description. The development of the direct import now reflects the immense design freedom afforded by RM and enables the potential inclusion of smart or fully optimised structures of any complexity. The following figures, Figure 14 & Figure 15, show the 3D geometric complexity that can now be achieved for RM textile RVE's and the resultant RM textile 3D data created by ChainLink.

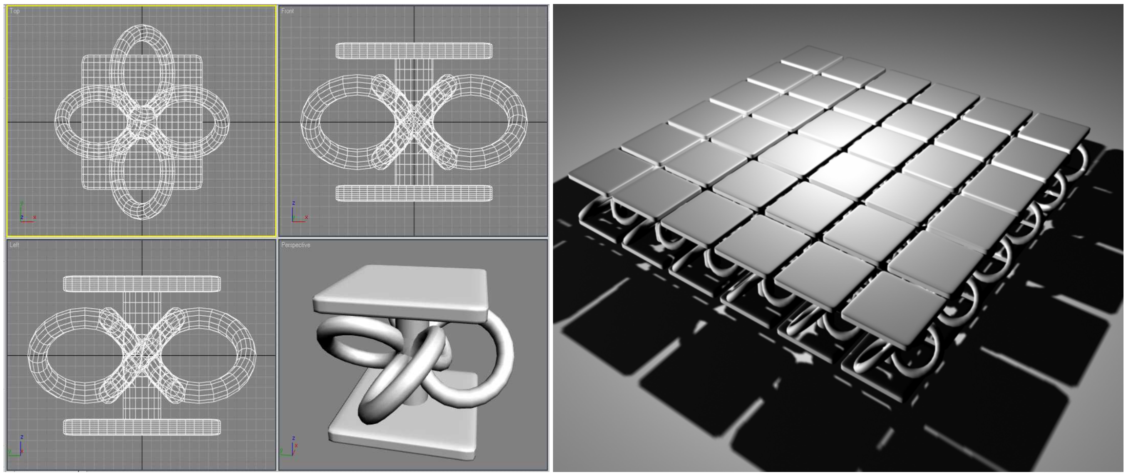

Figure 14: Complex RM textile RVE type 1 and resultant RM textile structure

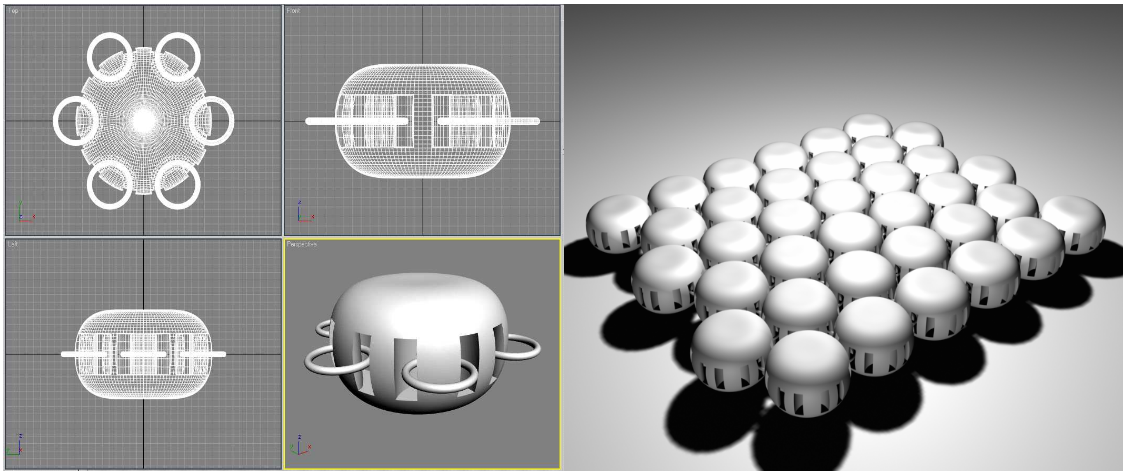

Figure 15: Complex RM textile RVE type 2 and resultant RM textile structure

New ChainLink Meshing Algorithm

The second limitation associated with adapted TexGen methodology was the dependency on FE created quadrilateral meshes. As previously discussed, commercial FE software does not have the required capability of creating a uniform mesh structure. This is mainly due to the intended use of FE meshes and the requirement to create an accurate mesh representation of the original 3D model for further analysis. This point is further exacerbated when creating triangular FE meshes. For the mesh to be equidistant, it must contain all equilateral triangles of the same dimension, and, to be fully uniform, an element to node ratio of 6:1, capabilities that are currently impossible utilising commercial FE software packages.

For RM textiles the requirement of the mesh is vastly different to the intended FE use. Here the requirement is a uniform mesh structure with nodal equidistance for the mapping of RM textile RVE's of the intended final net shape of the required article, not a comprehensive meshed representation for further analysis. Once this can be achieved, the resulting mapped RVE's of the RM textile will suffer no deformation or distortion, creating a fully uniform RM textile structure.

The aim of this section of the research was the creation of a triangular based meshing algorithm that can generate the required uniformity and equidistance for the subsequent mapping of RM textile RVE's via ChainLink. Several currently available meshing algorithms were investigated to ascertain any potential value or useable functionality. However, it was quickly established that no such available system would provide the required equidistance or uniform structure. To address this situation a completely new algorithm was required that would take into account the full requirements of RM textiles.

Initial experimental work has provided some encouraging results for the new meshing algorithm. As a comparison, a control 3D surface geometry was meshed using Fluent's Gambit FE meshing software [31] with a target triangular element size of 10mm using the 'paver' algorithm [32] and then again using the newly developed ChainLink meshing algorithm, using a triangular element size of 10mm. The results can be seen in Figure 16.

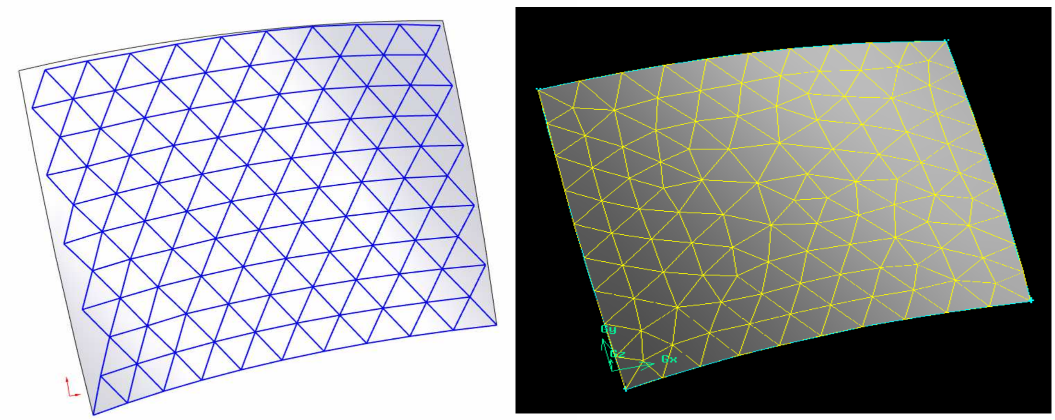

Figure 16: ChainLink algorithm created mesh left, Fluent's Gambit algorithm right

Figure 16 demonstrates the capability of each meshing algorithm. While the ChainLink algorithm does not fully cover the control 3D surface, as shown in Figure 16, it does mimic exactly how an actual RM textile would behave when draped over the same surface and provides a completely uniform mesh structure, which can not be seen in the Gambit created mesh. The actual dimensions of the elements produced can be seen in the following frequency charts of the two meshes, Figure 17 & Figure 18.

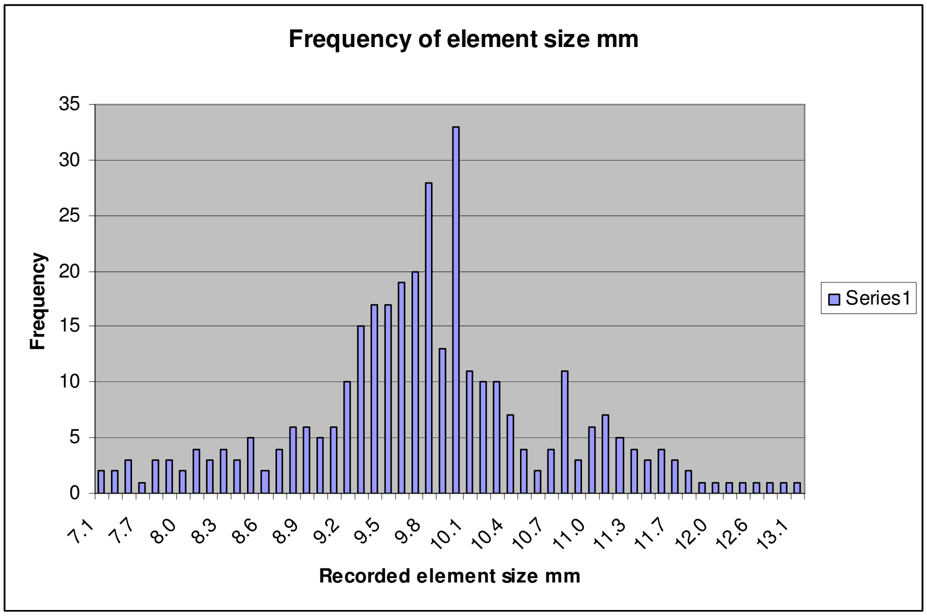

Figure 17: Frequency graph of recorded element size (mm), Gambit created mesh

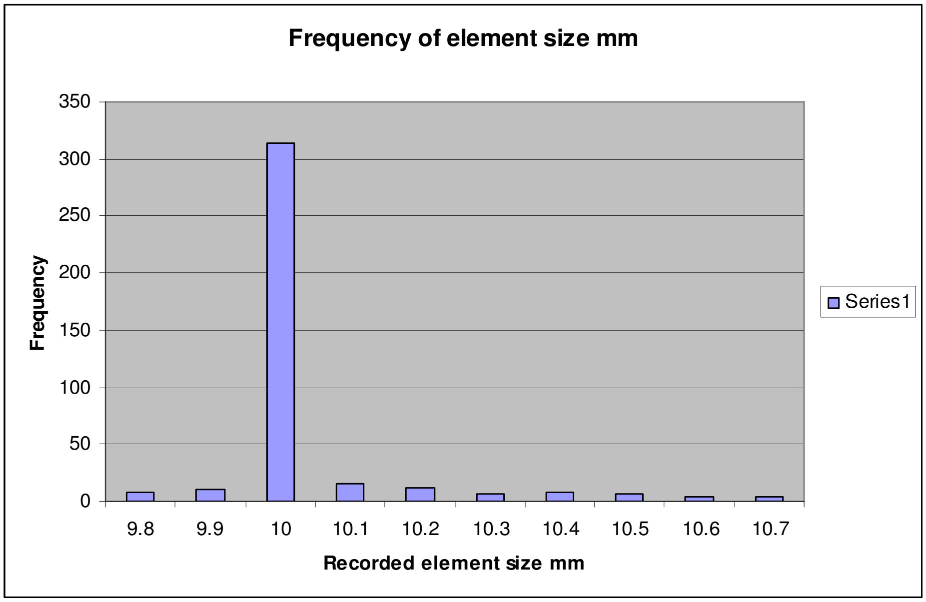

Figure 18: Frequency graph of recorded element size (mm), ChainLink created mesh

The two frequency charts of the respective meshing algorithms show the actual measurement of the elements produced and the frequency at which they occur. From the data it can be seen that the new meshing algorithm provides a substantial improvement over Gambits 'paver' algorithm, showing a range of less than +/- 0.7mm with the majority of the elements recorded at the target dimension of 10mm. The range recorded in element size of the 'paver' algorithm was shown to be at +/- 3mm with frequency spread more evenly across the entire recorded dimension range.

Conclusion

With the manufacture of textiles by Rapid Manufacturing techniques, incorporating its immense design freedom and unrivalled ability to manufacture geometry of increasing complexity without the need of tooling, the concept of designing textiles entirely for specific applications with no DFMA criteria becomes a manufacturing reality. The ability to manufacture textiles that are tailored to specific applications would enable the generation of new and hybrid textiles for a multitude of current applications and new applications only realised through the manufacture of functional specific RM textiles. In addition, the application of Rapid Manufacturing can enable the manufacture of fully finished customised items of clothing, new high-tech smart textiles capable of executing specifically designated tasks, components that transition from solid to textile, such as optimised footwear, and the potential to give textiles added functionality through design. If the paradigm of Rapid Manufactured functionally graded materials develops as predicted, the generation of smart clothing with integrated circuitry, sensors and actuators becomes entirely possible in one manufacturing process.

In summary, the initial work that has been undertaken so far has significantly advanced the subject area of RM textiles for the generation of smart and high performance textiles. The newly developed RM textile CAD tool has the capability to map any complexity of geometry to a FE created mesh. In addition, the newly developed meshing algorithm, soon to be incorporated into the ChainLink software, will eventually mean that any complexity of geometry can be mapped with uniformity and equidistance across any targeted curved geometry for the creation of conformal smart and high performance RM textiles.

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