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Hybrid ants: A new approach for geometry creation for additive and hybrid manufacturing

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Abstract

This research presents a novel and disruptive approach to the simultaneous design and structural refinement of parts manufactured using purely additive, purely subtractive and hybrid additive-subtractive manufacturing processes (HASPs). This research is responding to the increasing need to be able to state with confidence that a particular part design can be manufactured by a particular process. This is viewed as a major barrier to the profitable exploitation of additive and hybrid manufacturing processes. By describing the known part constraints and the mechanisms (limitations) of constituent manufacturing processes, parts are designed using a bio-inspired multi-agent system called 'Hybrid Ants'. By abstracting manufacturing processes into a set of rules that limit how and where material can be processed, all part geometries created by the Hybrid Ants are inherently 'manufacturable' under the current description of the manufacturing capability. The possibility that new knowledge may be elicited from this system is an exciting new paradigm, which could change the way design for additive (or hybrid) manufacturing processes is developed in the future. As will be shown throughout this paper, Hybrid Ants is a closed-loop system, which generatively creates part geometries and then appraises these geometries for structural performance using the finite element method. Stress values are then used in the next loop iteration to refine the geometry ad infinitum. This system is akin to ant (or termite) nest morphogenesis, where nest layouts are optimised for thermoregulation and ventilation. In this research, thermoregulation is analogously exchanged for stress for structural optimisation of engineering components.

Keywords: Generative Design; Multi-Agent System; Additive Manufacturing; Hybrid Manufacturing Processes; Design for Additive Manufacturing

1. Introduction

Additive and hybrid (additive and subtractive) manufacturing processes have unlocked previously unattainable levels of complexity in engineering component geometry. At the present time, the engineering bottle-neck no longer resides in 'what can be manufactured' but rather, 'what can be imagined and validated'. Doubrovski et al. [1] categorise the advantages of additive manufacturing processes as follows: part consolidation, mass reduction, functional customisation, personalisation and aesthetics. Gibson and Rosen [2] describe the advantages of AM as being: suitability for complex and customised geometries, part consolidation and avoidance of limiting manufacturing constraints associated with traditional manufacturing processes. Benefits also exist in the use of materials that are otherwise difficult to process, such as aerospace-grade alloys and inter-metallics.

AM and hybrid processes have brought about a new era of design, whereby component geometries are created and analysed via mathematics, rather than drawing tools and prior knowledge. Increasingly popular examples include topology optimisation and the use of cellular (lattice) structures to extract enhanced engineering performance by optimising material layout, whilst minimising a part's mass. However, in order for businesses to economically tap into the advantages of AM and hybrid processes, whilst using the state-of-the-art in design tools, they must be able to appraise increasingly complex part geometries for manufacturability. Attempts to industrialise metal AM has created awareness of a number of different manufacturing limitations. A well-recognised example is the

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avoidance of overhanging features in additive manufacturing, so as to avoid the need for support structure. Also appropriate care when specifying high-aspect ratio geometries and volumes of material that are prone the build-up of residual stresses.

Brackett et al. [3] identify several methods for conducting TO, including Solid Isotropic Material with Penalisation (SIMP), bidirectional evolutionary structural optimisation (BESO), level set methods and genetic algorithms. The same authors [3] describe two general methods to inforce manufacturing constraints upon TO, whereby the TO is limited to only produce feasible geometries, or the as-optimised geometry is retrospectively simplified to improve manufacturability. The latter is somewhat inefficient, as significant deviations from the as-optimised geometry may be required to secure manufacturability. This risks compromising the optimality or accepting a loss of design intent. Either way, the marriage between TO and manufacturability is far from harmonious.

A popular manufacturability check for TO concerning an additive process is the avoidance of excessively overhanging features. Here, TO is conducted on a regular square [4, 5] or cubic grid [6], with a filtering kernel to remove or prevent overhanging geometry creation. Other methods have utilised Pareto TO to create 'manufacturable' additive geometries, showing the relationships between volume fraction, support volume and component compliance [7]. Research has also addressed the use of TO in conjunction with 2.5D machining operations [8] and a hybrid combination of additive manufacturing and 2.5D machining [9]. In each of these research efforts, additively processed materials is generated in a freeform method via SIMP-TO. Features identified for CNC machining are constrained to be 2.5D features, as recognised by a feature-fitting algorithm.

Each of these methods addresses a single important aspect of design for additive or hybrid manufacture. However, the future of this field requires simultaneous appraisal of multiple manufacturing constraints. No such framework has been identified in the literature, where an arbitrary number of manufacturing constraints are combined and layered to give a more holistic statement of manufacturability. In response to this critique, this paper describes a novel, multi-agent generative design software to conduct structural optimisation for additive, subtractive and hybrid additive and subtractive manufacturing processes. Here, inspiration has been taken from ant and termite nest morphogenesis, were complex structures are generatively created by a colony, optimising for ventilation or thermoregulation [10–12]. Structural stiffness has been analogously exchanged for ventilation for use with engineering components.

The architecture can accept any manufacturing constraint that can be evaluated spatially across a three-dimensional voxel grid. This includes but is in no way limited to: tool-accessibility, minimisation of support structure and avoidance of excessively overhanging features in additive manufacturing. This research contributes a design tool that accepts a computer readable description of a part's functional requirements and a series of manufacturing rules that are used to create parts in a generative manner. This approach means that part geometries are inherently 'manufacturable' under a predetermined description of the manufacturing process(es). Hence, the usefulness of this software is a reflection of the granularity with which the functional requirements and the manufacturing capabilities are described. Users with different manufacturing capabilities will generate quite different geometries. By abstracting the manufacturing processes and structural optimisation this system attempts to capture what was previously regarded as human engineering expertise. As the system develops further, it is not yet known what new design techniques and feature geometries will become known to us, the design and manufacturing community.

2. Hybrid Ants Architecture and Framework

The architecture of the Hybrid Ants system is detailed in Figure 2. This system has been implemented in the Java programming language and interfaces with the Karamba3D (FEA) plugin within Grasshopper, which operates alongside Rhino3D version 5. Additionally, the overarching algorithm is described by the pseudocode listed in Figure 1.

```
WHILE manufacturing requirements are not met
  WHILE a source of pheromone still exists
    FOR each Ant in Colony
      MOVE ant
      IF complies with manufacturing rules
        PROCESS material
      ENDIF
      REMOVE pheromones within diffusion radius
    ENDFOR
    CALCULATE stress in generated part using FEA
    IF manufacturing requirements not met
      CREATE new Pheromones from normalized stress data
      ADJUST sensitivity to pheromone scents
      RESPAWN Ants onto baseplate
      DELETE all material
    ELSE
      SAVE geometry of generated part
    ENDIF
  ENDWHILE
ENDWHILE
```

Fig. 1: Pseudocode representation of the MAGGS system's iterative loop

2.1. Voxel World

In order to create solid geometries without unwanted porosity, it is essential that material can be added and subtracted at discrete layer heights, whilst creating a regular tiling in three-dimensional space. The cube is the only regular polyhedron that provides three-dimensional tiling and, hence, is the most basic element in what shall be termed the 'voxel world'. All voxels have position and size properties, with all voxels sharing a common size. This size governs the resolution of the part geometries that are created. Depending on the degrees of freedom exhibited by a manufacturing process, each of the six sides of the cube can be used for traversal and material processing during manufacture. The processing of material via a manufacturing operation is conducted by a bio-inspired multi-agent system, known as the 'ant colony'.

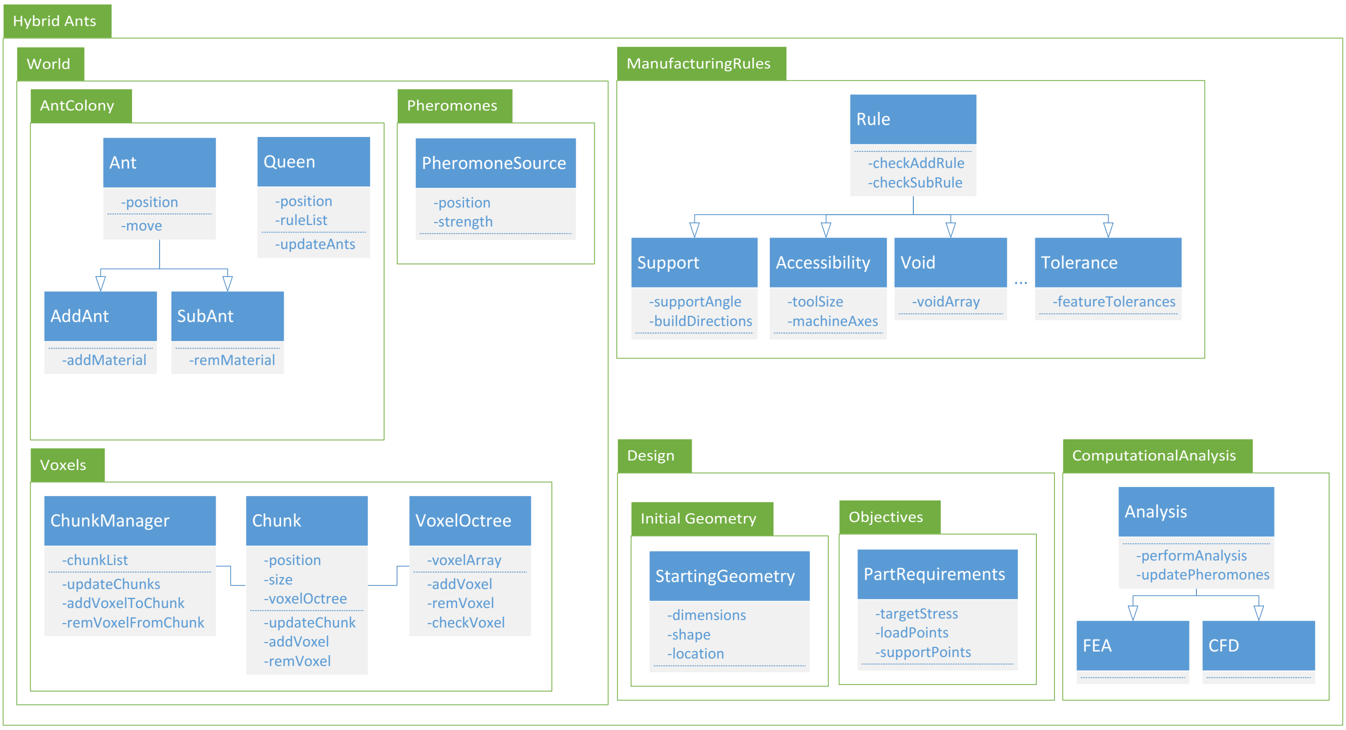

Fig. 2. The Hybrid Ants software architecture, as implemented in the Java programming language

2.2. The Ant Colony and Pheromone Trails

A single agent, or ant, can move within the voxel world in using taxicab motion. Ants are always positioned at the centre of a cubic element, but can be orientated to face each of the six faces. This orientation is used to change direction within the world, but is also used to change the direction in which they process material. As such, not all orientations can be used to process material, which reflects the degrees of freedom of a particular manufacturing process. For example, in three-axis machining the axis of the cutting tool must always be parallel to the Z-direction. The colony is governed by a 'Queen'. The queen creates ants on the build plate surface(s), destroys ants that have failed to either move or process for a fixed number of time-steps, holds the pheromone map to issue movement instructions for each worker-ant and issues commands for each ant to perform its particular process.

Ants roam throughout the voxel world, checking with every move to see if they can perform their designated manufacturing operation. For example, additive and subtractive ants seek to add or remove material one cubic element at a time. Much like ants in nature, they follow pheromone trails, which become stronger or weaker depending on the need for a particular manufacturing process. The strength of the pheromone relates directly to the statistical probability of a particular ant performing a manufacturing process in that location (random draw). If it is deemed that an ant should process, it must then check to see if it is in contravention of any of the rules of manufacturability (e.g. don't attempt to deposit new material that is not attached to any pre-existing material).

The motion of all ants is governed by the same mechanism. Let $D_{(i,j,k)}$ denote the distance of the ith ant from the jth pheromone source, given that the ant makes the kth move.

$$D_{(i,j,k)} = \left\| \boldsymbol{v}_j - (\boldsymbol{v}_i + \boldsymbol{v}_k) \right\|_1 \tag{1}$$

where $\boldsymbol{v}_i$ is position of the ith ant, $\boldsymbol{v}_j$ is the position of the jth pheromone source and $\boldsymbol{v}_k$ describes the vector movement of the kth move. Here, $\|\boldsymbol{x}\|_1$ is the taxicab norm of the vector $\boldsymbol{x}$. This distance quantity is then used to calculate the total strength of all pheromone scents acting on the ith ant once it has made the jth move, which shall be denoted $\gamma_{i,k}$.

$$\gamma_{(i,k)} = \sum_{j=0}^{J} \frac{\rho_k \, s_j}{1 + D_{(i,j,k)}} \tag{2}$$

ρ_k is the density of the material currently occupying the position of the ant once it has made the kth move, s_j is the strength of the jth pheromone source at its origin, and J is the total number of pheromone sources minus one (zero indexing). The value $\gamma_{(i,k)}$ is finally used to calculate the probability of the ith ant making the kth move from its current location.

$$P_{(i,k)} = \frac{\gamma_{(i,k)} r_{i,k}^A}{\sum_{k=0}^{K} \gamma_{i,k} \, r_{i,k}^A} \tag{3}$$

These probabilities are then used to select which of the K total possible moves, the ith ant makes via a random draw. In (3), $r_{i,k}^A$ is the ascending rank for the increase in pheromone strength for each of the K possible moves, raised to the power A. By increasing A, the likelihood of the ith ant making a move in the direction of the strongest pheromone scent increases substantially. Therefore, when pheromone sources reflect the distribution of stress in the part, ants are more likely to deposit in the vicinity of the high-stress regions. A is set in accordance with the principles of proportional control:

$$A_{n+1} = K_p\left(\frac{F_y}{s_f} - F_{max}\right) + A_n \tag{4}$$

Here, A_{n+1} is the exponent used in the next iteration, K_p is a proportional gain, F_y is the yield stress of the material, s_f is a factor of safety, F_{max} is the maximum stress arising in the FEA and A_n is the exponent in the current iteration.

Once the ant has moved, it is then determined whether the ant should perform its manufacturing process. This is again a matter of probability. For an additive process, (2) and (3) are reused with modification. The parameter $\gamma_{(i,k)}$ is replaced with $\sigma_{(i,k)}$, which is a measure of the need for the i^{th} ant to perform a process having made the k^{th} move.

$$\sigma_{(i,k)} = \sum_{j=0}^{J} \frac{(1-\rho_k)\, s_j}{1 + D_{(i,j,k)}} \tag{5}$$

This is then used in a similar manner to (3) to calculate the probability of performing a manufacturing operation in situ. The exponent, A, is calculated as in (4).

$$P^*_{(i,k)} = \frac{\sigma_{(i,k)} r_{i,k}^{A}}{\sum_{k=0}^{K} \gamma_{i,k}\, r_{i,k}^{A}} \tag{6}$$

Figure 3 gives a two-dimensional example of an ant in the vicinity of two pheromone sources (black shading) of strengths one and two. The four possible moves for the ant are denoted using the '#' symbol. Grey shading is used to show regions that currently have material in situ. Using (1)-(3), the percentage chance of the ant moving to positions #0, #1, #2 or #3 are 12.57%, 86.79% 0% and 0.64%, respectively, when A is set to 4. This shows the preference towards the intuitive move towards the pheromone sources.

It has been recognised that ants predominantly do 'productive' work when they are travelling and processing within the feasible envelope of a given process. For the additive process considered in this paper, this means ants should be moving and processing between ±45° to the build direction. Ants operating outside of this envelope tend to unnecessarily thicken material or fail to process at all. Hence, equation (3) is used to calculate the resultant vector in which an ant wishes to travel and process. If this vector falls outside the envelope of ±45° to the build direction, the ant is killed and respawned on the base-plate.

2.3. Rules for Manufacturability

Hybrid Ants is a system that can accommodate purely additive, purely subtractive (CNC machining) and a combination of the two processes into a hybrid process, such as that seen with in-envelope hybrid machine tools as detailed in Flynn et al. [13]. The rules of manufacturability are as follows: A cubic element of material may be added if there is sufficient support material beneath it. If the additive process can accommodate an overhang of 45° to the build direction before requiring support structure, there must be material directly beneath or diagonally beneath the newly added material in the direction of processing. There must be line-of-sight access to the processing location in the direction of processing. This can be represented as a cylindrical column of empty space above the position of the new material, extending to the edge of the design space. This can be an arbitrary geometry to better reflect the hardware being utilised. In addition to this, both additive and subtractive processes should avoid processing already processed material i.e. don't add material where material already exists and do not attempt to cut empty space.

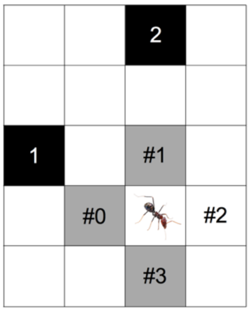

Fig. 3. A 2D example decision scenario for an ant in the vicinity of two pheromone sources (black) of strengths one and two, with four available moves (#) and surrounding material (grey).

A subtractive process requires line-of-sight access to the point of processing, using a column that represents the cutting tool geometry. Further to this, subtractive processes should not divide a single workpiece into multiple workpieces. This is checked using a depth-first search of the tree structure defining all existing cubes of material and their connectivity. If this search identifies multiple connected tree structures, the part has been divided. It should be noted that connectivity can be established through the build plate, to permit the simultaneous construction of multiple columns that are later joined.

2.4. Part Requirements

The major purpose of this development is to be able to simultaneously conduct structural optimisation of a part's geometry, whilst maintaining an uncompromised statement of manufacturability. Parts are designed in a generative fashion, using only a computer-readable description of the functional requirements of the part. At the present time, functional requirements include voids, which are regions in which material cannot exist. This includes, but is not limited to: tooling access, holes for fasteners, flat surfaces for location and mating, inlet and outlet ports for fluid flow and the geometry of peripheral subsystems. Additionally, the ability to withstand a particular loading condition without exceeding a specified stress. Finally, manufacturing requirements, such as avoiding the use of support material, are also included. This prevents the creation of excessively overhanging geometries. Furthermore, a starting point for the generative design can be specified as being an empty build-plate, a standard billet geometry or a pre-existing part geometry for remanufacturing and reincarnation via hybrid manufacturing.

The part geometry is built using voxels of a fixed size, which also doubles as hexahedral mesh of the part for finite element (structural) analysis. The corners of each voxel form the nodes of an eight node hexahedral element. These nodes act as attachment points for constraints and loads, as part of the functional requirements for the engineering component.

3. Implementation and Analysis

To illustrate the capability of the Hybrid Ants system, example requirements for a mechanical component are given. This example is for a bracket that extends away from a wall or other mounting surface, supporting a cantilevered load at a fixed distance from the wall. Ants are spawned on the attachment plate to the wall in four circular locating regions. A schematic of this set-up is given in Figure 5. The build direction of the component is also shown in this schematic.

The Hybrid Ants ran for a total of 27 iterations of generative geometry creation and subsequent finite element analysis to create stress-fields. Renderings of the resulting geometries for the first, eighteenth and final iterations are given along with the maximum stress and volume fraction for the parts in Figure 6. From inspection of the images and statistics in Figure 6, several behaviours are clear. Firstly, the load-bearing end of the cantilevered structure has been successfully connected to the mounting plate. Secondly, as the iterations progress, there is an obvious tendency towards thinning the structures and the establishment of separated ‘legs’ extending from the mounting plate. Two photographs are shown in Figure 7 showing geometry created from Figure 6c and another example for the same set-up but supporting half of the specified load. Both parts uphold the manufacturability criterion of avoiding support structure in the specified build direction. This was validated on an Ultimaker 2+ Extended using the FDM process.

The progression of the maximum stress and volume fraction of the designed geometries is shown in Figure 8. This graph also shows the target maximum stress for the design. The volume fraction clearly drops rapidly in the first few iterations and then stabilizes between 0.12 and 0.13. These values show significant light-weighting opportunities are available through the use of Hybrid Ants. The maximum stress experienced by the parts initially increases towards the target stress and then oscillates around the target value. Figure 9 gives examples of the stress distributions and corresponding pheromone maps that were created for the 18th iteration. Care must be taken to avoid selecting geometry that falls marginally above the designed maximum stress threshold. As such, it is important to compare both volume fraction and maximum stress when selecting a geometry. Hybrid Ants can rapidly generate multiple, viable geometry solutions and is showing initial indications of geometry refinement, such as that seen in more conventional topology optimisation. It is, however, clear that further refinement of the geometries is necessary. As such, there is a need for smoothing algorithms that do not compromise the absolute statement of manufacturability.

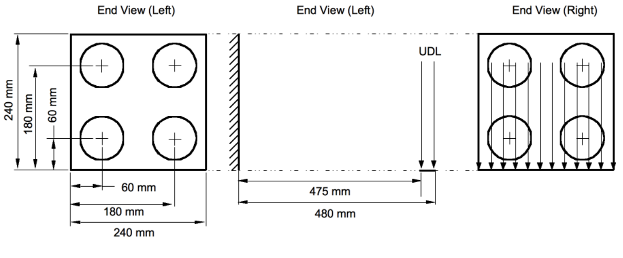

Fig. 4. Part function requirements for demonstration

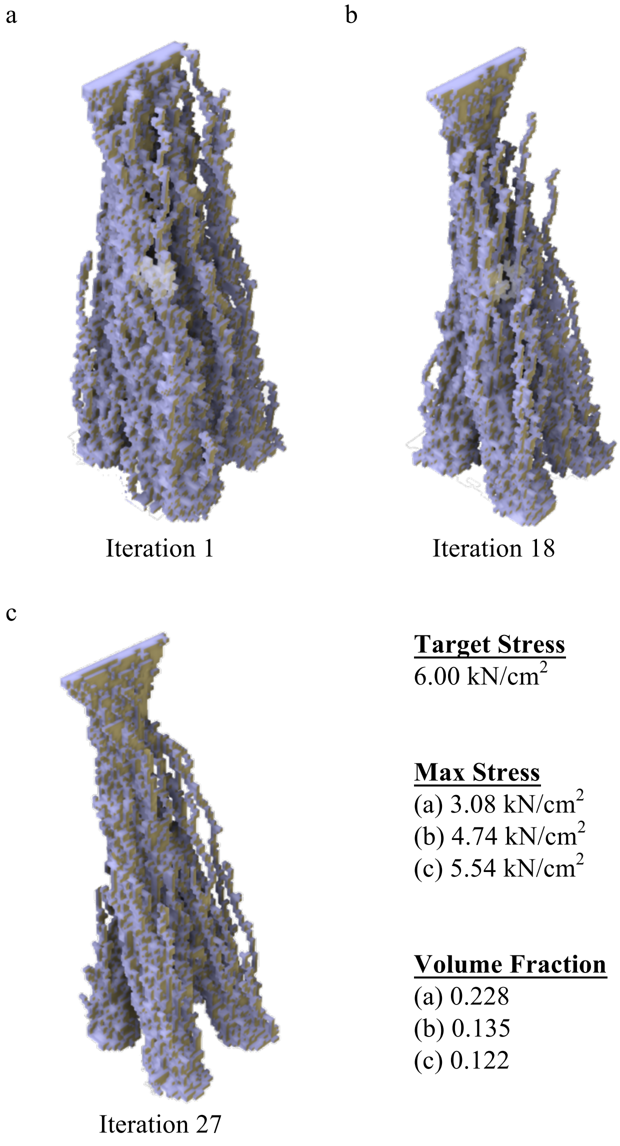

Fig. 5. Geometries created by the Hybrid Ants for the specified part (Figure 5) description at iterations (a) 1; (b) 18; (c) 27

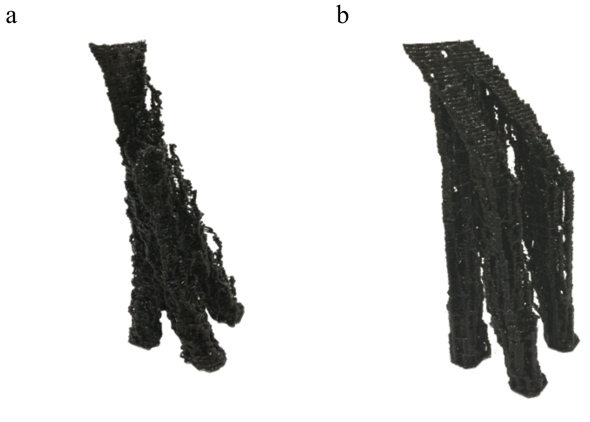

Fig. 6. Two photographed parts, manufactured using the Ultimaker+ Extended for (a) maximal load; (b) half-maximal load

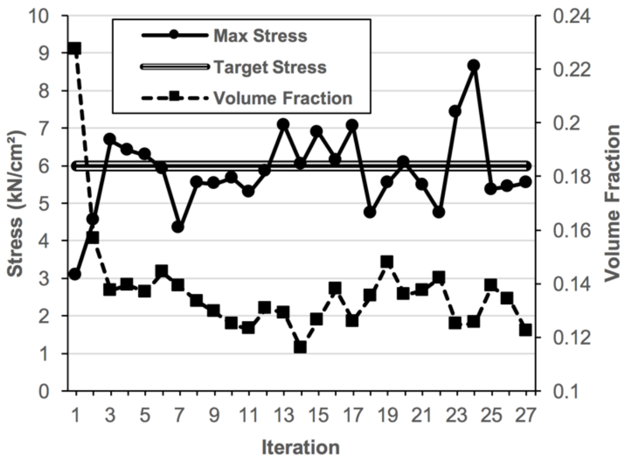

Fig. 7. Progression of maximum stress and volume fraction across 27 Hybrid Ants iterations for the part specified in Figure 5

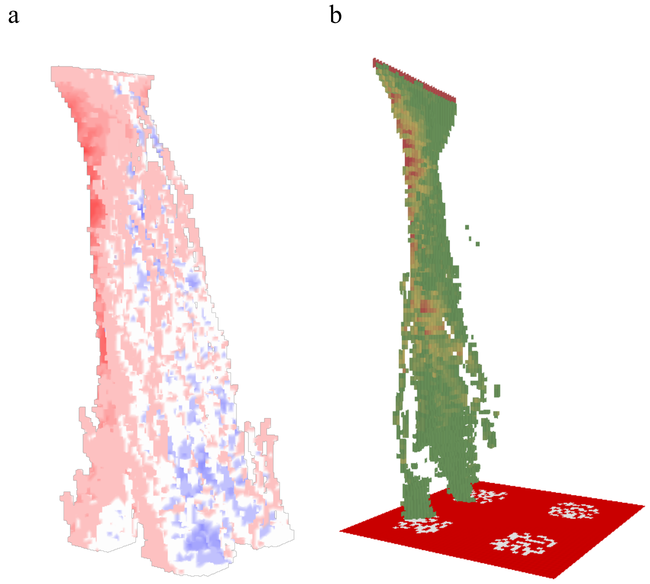

Fig. 8. (a) Colour-coded stress field from Karamba3D finite element analysis; (b) Associated pheromone map for the next Hybrid Ants iteration

4. Conclusions and Future Work

For the first time, this research has created a bio-inspired multi-agent generative design tool for parts manufactured using either an additive, subtractive or hybrid additive-subtractive process. Furthermore, it has been shown that the Hybrid Ants system is capable of light-weighting structures whilst firmly adhering to manufacturability constraints. The significance of this method is that parts may now be designed using only a description of the parts functional requirements and the manufacturing process capability. The major contributions of this research are the Hybrid Ants architecture and a method to iteratively refine geometries using finite element analysis. Additionally, it shifts the design focus towards a description of the part's functional requirements and manufacturing process capability and away from the creation of complex geometries using individual creativity and expertise.

Looking to the future, there are four avenues of further development for this research. Firstly, physical testing of manufactured parts design using the Hybrid Ants system must be conducted to demonstrate a correlation between the structural performance of designed and manufactured parts. Secondly, the development of porosity and defect correction algorithms (filtering and smoothing) is necessary to create a manufacturing process-aware smoothing capability for final part geometries. Special care must be taken to ensure that these algorithms do not compromise the statement of manufacturability. Finally, demonstrations of part manufacture on a truly hybrid machine tool will form the final validation of the proposed system.

Acknowledgements

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