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A generative multi-agent design methodology for additively manufactured parts inspired by termite nest building

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The geometrical complexity available through additive manufacturing processes requires new tools to help designers maximise its advantages. A termite colony can construct highly complex nests that are optimised for thermoregulation and ventilation. The simple individual behaviour of these termites leads to highly intelligent colony behaviour, allowing nests to be simultaneously designed, optimised and produced. By mimicking termite behaviour, this research has led to a new design methodology using multi-agent algorithms that simultaneously design, structurally optimise and appraise the manufacturability of parts produced by additive manufacturing. A case study demonstrates the generative design of lightweight parts using the multi-agent system.

Design Method, Algorithm, Generative Design

1. Introduction

Additive manufacturing (AM) processes promise to unlock unprecedented levels of design freedom via layer-wise manufacture. This freedom could lead to step-changes in the complexity and performance of parts and products. However, the question remains – are we equipped to comprehend and leverage this level of complexity and design freedom?

The ability to manufacture almost any shape with hierarchical complexity (macro geometry, meso-material properties such as lattices, and custom microstructures or metallurgies) means that the design space for AM is vast [1, 2]. Furthermore, complex relationships exist between part geometry and part 'manufacturability'. For example, the orientation of the part with respect to the build direction can significantly influence material and energy usage [3]. Also, the build-up of residual stress within a part is often difficult to predict [4], which can result in costly in-build or in-service failures.

In 2008, a call was made for new tools to support designers as they pursue optimal designs within highly complex design spaces [5]. This is increasingly poignant in connection with industrialised AM. Successful design for AM (DfAM) relies on an increasing overlap between engineering design, materials science and manufacturing. One reason for this is the lack of opportunities for human intervention during the manufacturing process [6]. The pressing need to consider the effects that design changes have on downstream processes requires engineering with AM to be more integrated or even concurrent. These notions have been explicitly identified in the 2016 CIRP Annals Keynote on Design for Additive Manufacturing (DfAM), stating:

"The coupling between the design, representation, analysis, optimisation, and manufacture still needs to be resolved." [6]

This paper aims to address this statement directly by taking inspiration from nature, which has proven to be a fruitful source of inspiration in engineering design [7]. Termite nests are highly complex and can be optimised for ventilation or thermo-regulation. This is achieved without any intelligible architectural oversight [8]. The existence of termite nests is testament to the fact that they are inherently 'manufacturable'. This paper presents a design method that mimics the behaviour of termites as they build their nests, to concurrently design, structurally optimise and appraise the manufacturability of AM parts.

2. Background

As industry aims to increasingly utilise AM, there is a risk that the design process will not be objective or exploratory. Prior experience with traditional manufacturing processes, subconscious bias or prejudice towards a particular aesthetic or layout, and the risk of design fixation may all compromise the objectivity of an AM part design [9]. This may be heightened by time consuming developmental and optimisation cycles.

Throughout the 1970-80s, traditional manufacturing processes (e.g. machining or casting) benefited from the introduction of Design for Manufacture and Assembly (DfMA) [10]. Since the emergence and proliferation of AM, research has tried to adapt the DfMA guidelines to accommodate AM processes; however, these have struggled to capture the integrated nature of designing parts for AM [11, 12]. Consequently, a body of research is amassing in the use of more flexible tools that aim to search more broadly through large design spaces, or target optimal designs.

Generative design tools that create concepts from requirements, constraints and goals are viewed as one way to be more exploratory and objective [13]. Autodesk describe four types of generative design tools that are emerging in field of DfAM: form synthesis, lattice and surface optimisation, topology optimisation and trabecular structures [14]. These methods may be regarded as design-by-search, or design-by-optimisation. However, this mathematical approach often fails to incorporate human interaction and oversight throughout the design process. Recent research has tried to address this issue via human-computer interaction within generative design tools [15].

It is the authors' contention that although generative design methods are emerging as a popular approach for DfAM, they too are currently failing to couple design, representation, analysis, optimisation and manufacture. As such, the authors have developed a new, multi-agent generative design tool. The architecture of the software and its overall approach are published separately in [16].

The system receives a description of the part's functional requirements and the available manufacturing capabilities as inputs. Many agents, or termites, generatively construct geometries by depositing material; always adhering to the design and manufacturing constraints. Integration with a finite element solver makes this a closed loop system, whereby the termites' behaviour is altered according to e.g. stress within the part. This paper reports on new findings regarding the governing dynamics of the system and its ability to convergence upon a final part concept.

3. The Governing Dynamics of the Termite Colony

Termites move throughout a three-dimensional world, constrained by taxicab geometry (i.e. no diagonal movements). This results in six possible directions of motion and the direction of each termite is determined using a random draw from these six options. Additionally, each termite may only move by one unit of length per move. To steer the subgroups of the colony to areas of interest, the probability of a termite making a certain move is manipulated according to two criteria: (i) The gradient of the pheromone field at each termite location, and (ii) the presence or absence of material in all possible subsequent locations for each termite (i.e. after their next move).

3.1. Behaviour Resulting from Pheromones

Pheromones are used to direct the termite colony. Termites are encouraged to move themselves, and build material towards, pheromone sources. The need to attract termites is initially to connect all part features using a single expanse of material. In addition, the integrated finite element analysis (FEA) converts stress magnitude into pheromone intensity, thereby encouraging termites to increase the amount of material in highly-stressed regions. Each pheromone source results in a field that diffuses across an n-dimensional space in which the part exists. At a given position, this field has an intensity, which relates to the proximity of the pheromone source. The intensity of the pheromone field at a given location is established via the summation of all individual pheromone effects. The intensity perceived at the location of the i^{th} termite is:

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

$$P_{(i,k)} = \frac{\gamma_{(i,k)} r_{i,k}^{A}}{\sum_{k=0}^{K} \gamma_{i,k}\, r_{i,k}^{A}} \quad (2)$$

s_j is the strength of the j^{th} pheromone at its origin. $D_{(i,j,k)}$ is the taxicab distance from the i^{th} termite to the j^{th} pheromone source, once it has moved in the k^{th} direction.

$$D_{(i,j,k)} = \left\| \boldsymbol{v}_j \text{-} (\boldsymbol{v}_i + \boldsymbol{v}_k) \right\|_1 \quad (3)$$

In an n-dimensional world, the k^{th} direction corresponds to the vector forming the k^{th} row matrix, $\boldsymbol{v}$:

$$\boldsymbol{v} = \begin{bmatrix} I_{n\times n} \\ \text{-}I_{n\times n} \end{bmatrix} \quad (4)$$

Termites may do one of two things, namely move to a new location or process material; first they move and then they process. The governing equations (1 and 2) behave differently depending on whether an ant is moving or processing. This is controlled by the conditional nature of the parameter, C:

$$C = \begin{cases} \rho_k, & a\ moving\ termite \\ (1-\rho_k)M, & a\ processing\ termite \end{cases} \quad (5)$$

Here, ρ_k is a binary operator that identifies whether material exists in the position of the termite once it has either moved or processed in the k^{th} direction. If material exists, it is set to one. The parameter, M, encompasses a set of manufacturability checks. These are discussed in Section 3.2. The elegance of, *C,* is that it represents the perceptive capabilities of the termites; telling them what is within their surroundings and, therefore, what their next available actions are.

The tendency of a termite to perform an action in the k^{th} direction is given by the instantaneous gradient of the pheromone field, $\nabla\gamma_{(i,k)}$. This is calculated numerically using central and one-sided differencing. It is not guaranteed that a termite will perform an action in the direction of steepest descent. Instead, this is controlled by a random draw. The probability of performing an action in the k^{th} direction is defined by Equation 2. Each probability is multiplied by a weight, which depends on the rank of the k^{th} move and the magnitude of the termite's "aggression," A. The A value is updated using an appropriate control law (proportional control). This determines whether the termites' behaviour is direct or exploratory.

3.2. Behaviour Resulting Manufacturing and Design Constraints

Termites are attracted towards high intensity pheromones. The actions the termites perform to reach the pheromones are dependent on manufacturing and design constraints for a particular problem. As seen in equations 1 and 5, termites only consider actions in a given direction if, *C,* is satisfied i.e. material is present in the k^{th} direction. For a termite to process material in a k^{th} direction, material must be absent as well as the parameter, *M*, being equal to one. *M* is a set of boolean operators representing all of the manufacturing constraints that must all be satisfied. The multiplication of each term ensures that *M* only has a value of one when all checks return a value of one. Any value of m_n will be zero if it fails its manufacturing check. Hence, if any of the manufacturing checks fail, *M* will also be zero. This prevents the termite from processing material in that direction.

$$M = m_1 \times m_2 \times m_3 \times \dots\ m_n \quad (6)$$

The list of manufacturing checks can be as detailed or general as is required. Some examples of manufacturing checks can be defined as follows: Is there material? Is there sufficient support material? Is there tool accessibility? Is material allowed? Minimum feature size? Feature aspect ratio?

By rigidly following these rules, termites are attracted towards pheromones and process material where needed but only in a way that simulates manufacture according to the rules set by the manufacturing constraints. Figure 1 illustrates the intensity field created by the pheromones, whilst also accounting for the manufacturing checks. Material is forbidden in the dark grey area, forcing termites away from this region.

3.3 Destroying Pheromone Sources

The need for a termite to directly deposit material upon a pheromone source reduces as the intensity of the pheromone reduces. This means that regions of, say, high stress require material to be placed exactly upon the origin of the associated pheromone source. In contrast a very weak pheromone source may be regarded as being 'satisfied' if material is placed within its vicinity. What motivates this behaviour is the desire to place material where it is strictly necessary; much like existing topology optimisation techniques. The conditions for removing a pheromone source are given by the inequalities in (7).

$$\left\|\boldsymbol{v}_{ij}\right\| \geq 0,\ \ s_j \geq 0,\ \ s_j < 1 - c_{kill}\left\|\boldsymbol{v}_{ij}\right\|_1^2 \quad (7)$$

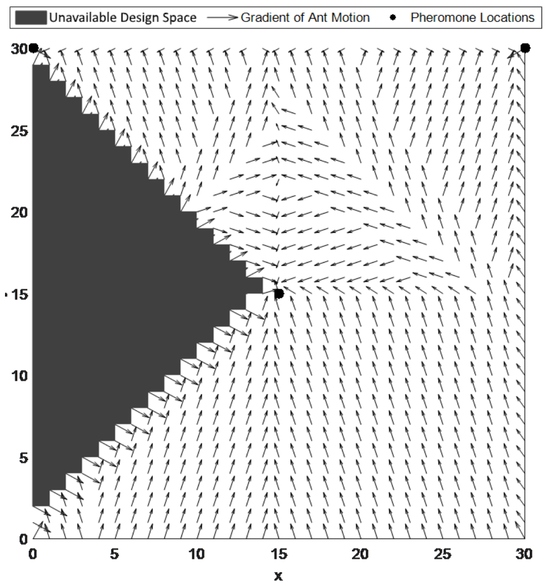


Figure 1. Gradient of termite motion affected by pheromones and manufacturing constraints.

4. Results: Converging on a Final Design

A colony of 2,000 termites was used to optimise a given design problem with respect to various objectives. An example design problem might include an envelope where material is permitted, a loading condition, and a more general objective to reduce the mass of the part. A fictional design problem is described in Figure 2, which shows three things. Firstly, solid white cylinders and spherical sections show regions in which material is not permitted (void-space). These might represent external subsystems that cannot be relocated, or access for maintenance tooling or wiring. In this example, the void-space is intentionally complex. Secondly, the black shading denotes the build plate and the build direction is normal to this surface. Finally, the hatched shading denotes a surface that will have a uniformly distributed compressive load applied to it, acting towards the build plate.

A feedback loop is established between the termite colony and a finite element solver. This allows closed-loop design iteration, where the termite colony outputs the current geometry and the FE solver converts this into a quantitative performance measure. This loop may continue ad infinitum, or until a stopping criterion is fulfilled. Stress values are fed back to the termite colony, where they are then converted into new pheromones, with intensity proportional to the stress magnitude.

To demonstrate that the system converges upon a final part geometry, two observation metrics are used. The first of these is the Hausdorff distance (d_H), which is taken as a measure of the similarity between the part geometries created in consecutive iterations of the algorithm. Here, the difference between the ith part geometry mesh (set Y) is compared against the ith-1 reference mesh (set X). The d_H between the two meshes is calculated based on the sets X and Y using (8)

$$d_H(X,Y) = \max\left\{\sup_{x\in X}\inf_{y\in Y} d(x,y), \sup_{y\in Y}\inf_{x\in X} d(x,y)\right\}, \quad (8)$$

Here, 'sup' and 'inf' are the supremum and the infimum, respectively. Consecutive meshes with a small d_H between them are considered to be more similar than those with larger values. The convergence of the d_H over a total of 60 iterations is shown in Figure 3, where the d_H is shown to reduce from 0.73 and settle at approximately 0.3. In addition to the d_H, the 'aggression' of the termites' (A, Equation 2) is also plotted. This value is initiated at 0.2 and then increases and eventually settles at approximately 3 over the course of the 60 iterations. This is in accordance with the proportional control law employed to set this value.

To demonstrate that the geometry from the 60th design iteration is inherently 'manufacturable' without support, the geometry was additively manufactured using an Ultimaker 2 Extended+ FDM printer using PLA (see Figure 4).

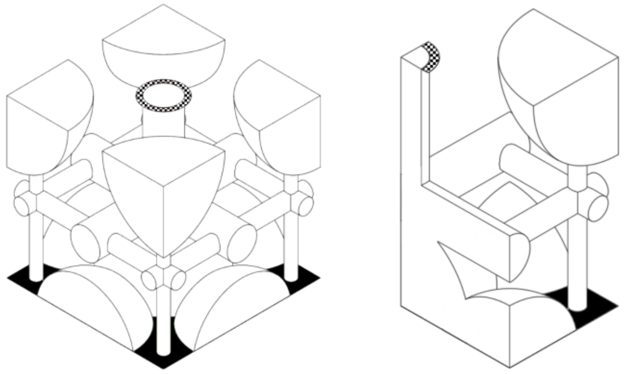
5. Discussion

The CIRP community has highlighted the need for a greater coupling between design, representation, analysis, optimisation, and manufacture in association with AM [6]. This paper has introduced a method for achieving this coupling via a generative, agent-based design tool. This tool migrates away from designing parts by drawing them, and moves towards designing parts by simulating their manufacture within a closed-loop design optimisation. This paper has demonstrated that parts designed this way are: (a) able to satisfy the functional requirements, such as load-bearing capability and avoidance of specific regions; (b) achieve an overarching design objective, such as reducing part mass; and (c) converge upon an overall volume and shape.

Given a fictional design problem (Section 4), the system designed a part that did not exceed the maximum permissible stress under compressive loading; 5.98MPa compared with 6MPa. The final part did not violate any of the spatial constraints imposed by the void space (Figure 2), and could also be manufactured without any supporting material. The final part (60th iteration) had a voxel count of 19,637 voxels. The total available volume in which material could exist (bounding box minus void-space volume) was 159,997 voxels. This represents a volume reduction of 88% when compared to the largest permissible geometry.

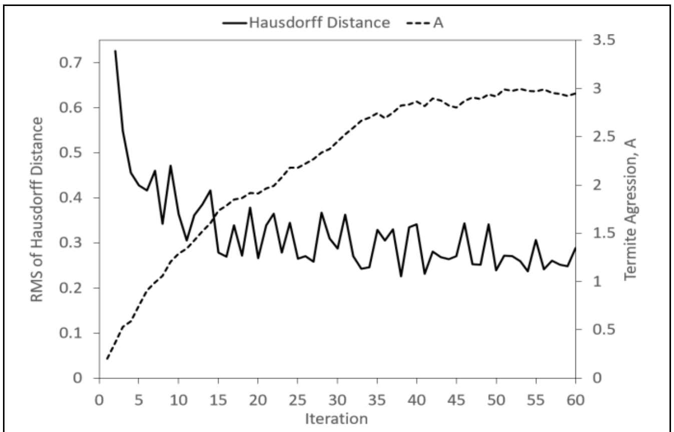
One of the advantages of the proposed system is that it concurrently designs, structurally optimises and appraises the manufacturability of a part. Furthermore, the number of design and manufacturing constraints and requirements can be increased or decreased at the user's discretion. The parts that are designed by the system are inherently 'manufacturable' under the given description of the process. It is proposed that more detailed descriptions of the manufacturing capability would permit greater confidence in the successful manufacture of the part. Sets of manufacturing rules can form profiles that can be interchanged for different machines, leading to different solutions to the same engineering problem. Finally, the system designs parts in a generative fashion i.e. without a starting geometry. Consequently, this system helps to alleviate bias, fixation and prejudices in the design phase, which has been highlighted as a major issue.

A prevailing limitation of the system is that it can only create geometry within a voxel world. This is only an approximation of the processing characteristics and material geometry.



(a) Full Void-Space (b) One Quadrant

Figure 2. The 'void-space' for proposed design problem.



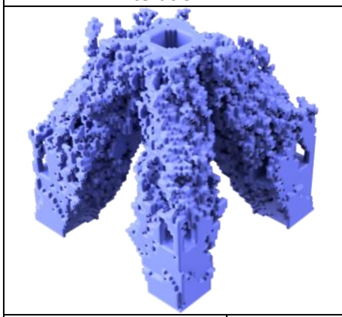
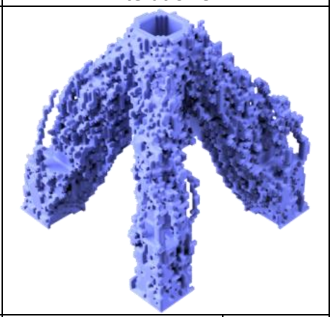
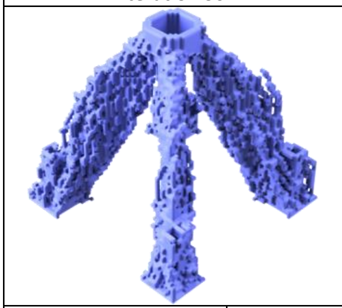
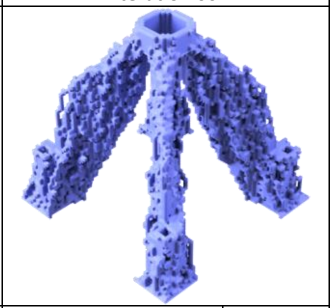
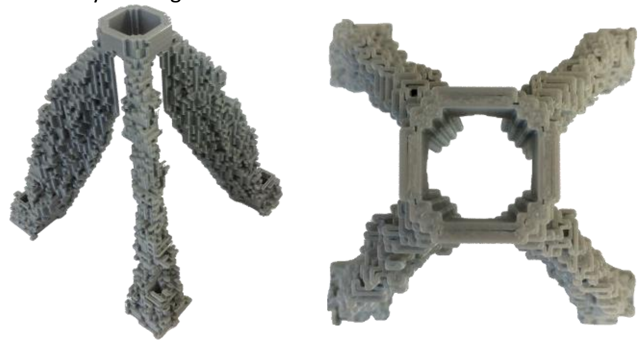
Iteration 1		Iteration 5	
			
No. Voxels	71,433	No. Voxels	43,043
% Volume Reduction	N/A	% Volume Reduction	40%
Iteration 30		**Iteration 60**	
			
No. Voxels	21,563	Voxels =	19,637
% Volume Reduction	70%	% Volume Reduction	73%

Figure 3. A plot of the Hausdorff distance between consecutive design iterations, and A value (Equation 2) for each iteration. Renderings of part geometries are shown in Figure 4.

Furthermore, the randomness of the termite behaviour leads to artefacts that do not necessarily contribute to the final performance of the part. Development of a manufacturing process-aware filtering and smoothing capability is therefore an immediate priority. Finally, the use of a fixed voxel size limits the resolution of the part features. New, adaptive meshing methods need to be employed to achieve variable resolution and to prevent the finite-element solver from becoming significant computational bottle-neck.

6. Conclusions and Future Perspectives

This paper has demonstrated that the agent-based, generative design tool is capable of simultaneously designing, structurally optimising and appraising the manufacturability of an AM concept part. The system converged upon a final part concept, with stable volume and shape. The system exploited opportunities to significantly light-weight the part, whilst preserving manufacturability and without compromising the required functionality. The significance of this research lies in the ability to create part concepts using only a description of the part's functional requirements and available manufacturing capabilities. This concurrent and generative approach represents a novel method for concept generation amidst the complexities of design for AM. This research will continue to build capabilities to handle increasingly complex design and manufacturing constraints. It will also focus on creating part concepts that can be manufactured reliably.



(a) Isometric View (b) Top View

Figure 4. A printed version of the geometry from the 60th design iteration.

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