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

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ABSTRACT

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.

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 thermoregulation. 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

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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 ith termite is:

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

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

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

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

In an n-dimensional world, the kth direction corresponds to the vector forming the kth row matrix, **v**:

$$\boldsymbol{v} = \begin{bmatrix} I_{n\times n} \\ -I_{n\times n} \end{bmatrix} \tag{4}$$

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:

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

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 kth 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 kth 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 kth direction is defined by Eq. (2). Each probability is multiplied by a weight, which depends on the rank of the kth 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 Eqs. (1) and (5), termites only consider actions in a given direction if, C, is satisfied i.e. material is present in the kth direction. For a termite to process material in a kth 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.

$$M = m_1 \times m_2 \times m_3 \times \cdots m_n \tag{6}$$

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. Fig. 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