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## 学位論文内容の要旨

A design problem is often characterized as a “wicked problem”, a term that describes challenges that involve epistemic uncertainty (uncertainty arising from a lack of knowledge) and a multitude of choices. Unlike well-defined problems, wicked problems or design problems do not have a clear or singular solution. The knowledge-intensiveness of a design problem can be made explicit by a design theory known as the C–K theory of design, where C stands for concepts and K stands for knowledge. The C–K theory of design offers two domains, the Concept (C) domain and the Knowledge (K) domain, to continue a design process. The spaces consist of propositions where the C domain deals with design solution-related propositions (concepts), and the K domain deals with propositions articulating the knowledge required to manifest the design solutions or concepts. This framework enables designers to systematically generate, expand, and validate new ideas as well as existing ones. This study applies the C–K theory to solve design problems relevant to reverse engineering (RE) and porous structures.

Conventional reverse engineering is concerned with the precise reconstruction of a given object in terms of its geometrical structure. For this, a conventional reverse engineering process scans the object using a non-contact scanning device and obtains a set of point clouds. The point clouds are then processed using complicated algorithms powered by sophisticated computer graphics systems to create a CAD model of the object. The large size, heterogeneous density, noise, and outliers associated with point clouds make conventional reverse engineering a highly skill-intensive and iterative process. Therefore, an alternative reverse engineering is needed to make reverse engineering more pragmatic. In this study, we have developed a novel reverse engineering approach using the C–K theory of design. The approach integrates three types of knowledge (creative definitional knowledge, informal inductive knowledge, and deductive knowledge).

These types of knowledge facilitate the generation of relatively small-size planner point clouds, capturing important features of the object to be reverse engineered. These point clouds can be easily converted to a computer-aided design (CAD) model to support the digitization and fabrication of the object. The efficacy of the proposed reverse engineering is demonstrated by reverse engineering a damaged gear-pinion set. This set cannot possibly be reconstructed using conventional reverse engineering. Unlike conventional reverse engineering, which focuses mainly on replicating a given object, this new approach takes a different path; it enables the creation of innovative solutions that achieve the same functionality as the original object. This shift from strict replication to creativity is a major advantage. Using this advantage, the proposed reverse engineering method can be applied to (for example) remanufacturing problems, which will be discussed in the next phase of this study.

Realistic porous structures consist of randomly distributed pores of different sizes and show advantageous properties compared to nonporous structures. These properties include a high surface area to volume ratio, selective permeability, and adjustable material characteristics. A common method for the design of porous structures uses scaffolds composed of regular geometric shapes known as unit cells. Scaffolds with randomly distributed pores of different sizes are difficult to design, and their fabrication faces challenges due to abrupt curvatures associated with the unit cells. An alternative design approach is necessary to enable control over pore distribution, size, and porosity while avoiding fabrication constraints. In this context, the C-K theory of design provides a theoretical foundation similar to that used in the previous case. This foundation introduces creative definitional knowledge, informal inductive knowledge, and deductive knowledge, which lead to three algorithms. It is shown that the algorithms can control the levels of self-similarity of fractal shapes such as the Sierpinski pentagon, the Dürer pentagon, and the McWorter pentigree and can represent the shapes by level-controlled point clouds. The point clouds can be converted into a CAD model using simple geometric operations such as rotation, extraction, addition, and subtraction. The efficacy of C-K theory-based porous structuring is demonstrated by creating CAD models of porous structures using the point clouds of the McWorter pentigree. The CAD model exhibits the desirable properties of a porous structure as mentioned before.

This thesis is organized as follows. Chapter 1 presents the background, context, scope, research objectives, and contribution of this study. Chapter 2 describes the C-K theory of design and presents a general description of knowledge. Chapter 3 describes conventional reverse engineering and a C-K theoretic formulation of reverse engineering, highlighting the avenues for improvement. Chapter 4 presents the details of the C-K theory-based reverse engineering as outlined above. Chapter 5 presents the details of the C-K theory-based, fractal geometry-driven porous structuring as outlined above. Chapter 6 discusses the implications of this study and highlights future research directions. Finally, Chapter 7 provides the concluding remarks of this thesis.

## 審査結果の要旨

設計問題は、知識の不足に起因する不確実性と多数の選択肢を伴う「ウィキッド・プロブレム」として特徴付けられることが多く、明確な唯一解を持たない。本研究では、このような知識集約的な設計問題に対し、概念空間 (C) と知識空間 (K) の相互作用として設計過程を記述する C-K 設計論に着目した。本論文では、C-K 設計論をリバースエンジニアリングおよび多孔質構造設計に適用し、創造的定義知識、非形式的帰納知識、ならびに演繹的知識を統合した新たな設計アプローチを提案した。リバースエンジニアリングにおいては、従来手法が抱える点群データの大規模性やノイズに起因する課題に対し、重要な形状特徴を抽出した小規模点群に基づく新しいプロセスを構築した。これにより、破損した歯車部品に対しても、機能的に代替可能な歯車設計が実現可能であることを示した。また、多孔質構造設計においては、フラクタル幾何学と C-K 設計論を組み合わせることで、気孔分布、気孔径、および構造連結性を制御可能な設計手法を提案した。提案手法により生成された点群は、回転、抽出、加算、減算といった基本的な幾何操作により CAD モデルへと変換可能であり、従来のユニットセル型およびランダム形状型多孔質構造と比較して、製造上の制約を低減できることを明らかにした。さらに、歯車および多孔質構造の両 CAD モデルについて 3D プリンティング技術を用いた試作を行い、いずれの構造についても製造上の問題なく造形可能であることを確認した。以上より、本研究は、C-K 設計論に基づく設計思考が、形状の単純な再現にとどまらず、創造的かつ実用的な設計および製造プロセスの構築に有効であることを明らかにした。これらの研究成果は、**Research in Engineering Design** をはじめとする国際的に評価の高い学術誌ならびに国内外の学術会議において発表されている。

よって、提出された学位論文の内容および該当する学術論文の質等を総合的に考慮した結果、申請者は北見工業大学博士 (工学) の学位を授与される資格を有する者であると認める。