ϕ = configuration angle of the translating follower or angular displacement of the oscillating follower

$\dot{\phi}, \ddot{\phi}$ = the 1st and 2nd derivative of the ϕ with respect to time

ω = angular velocity of the cam

ρ = radius of curvature of the cam

Δ_P = step for searching contact points

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Layout Optimization of Shapeable Components With Extended Pattern Search Applied to Transmission Design

Su Yin
e-mail: yin@andrew.cmu.edu

Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Jonathan Cagan
e-mail: cagan@cmu.edu

Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Peter Hodges
e-mail: phodges1@ford.com

Product Design Engineer, Vehicle Systems Engineering, Ford Motor Company, Dearborn, MI 48121, USA

An extended pattern search algorithm is presented for the placement of shapeable components within a product layout. Shapeable octrees are used to evaluate the amount of overlap between pairs of components, extending previous technology that requires fixed-size components. The method is used to conceptualize the layout of the cross-section of an automatic transmission.
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1 Introduction

In previous work, Yin and Cagan [1] introduced an Extended Pattern Search (EPS) algorithm for component layout that demonstrated a marked improvement over the previous state-of-the-art. Component placement or intelligent packaging finds application in many different applications. A summary of those applications and a review of the literature in this area can be found in the survey by Cagan, et al. [2]. In the previous work on the EPS method, all components had fixed-sized geometry, required to create octrees used for hierarchical geometry representation of fixed shapes. Many applications, however, require geometries to change shape during their placement. One such example is in automatic transmission layout where clutches must be sized for each location based on performance requirements.

In this note, the EPS algorithm is extended to include shapeable components. This note also introduces a new problem to the layout literature with the conceptual design of automatic transmissions. First the paper briefly summarizes the EPS algorithm. Next *shapeable octrees* are introduced. Finally the automatic transmission problem is presented and solved using the shapeable component EPS algorithm.

2 The Extended Pattern Search Layout Algorithm

2.1 The Extended Pattern Search Algorithm. The basic pattern search algorithms (Hooke and Jeeves [3]; Torczon and Trosset [4]) search for optimal solutions in the design space following a series of exploratory moves that rely exclusively on the direct comparison of function values, thus providing a tool suitable for the exploration of a design space that is nonlinear and discontinuous. Yin and Cagan [1] extended the basic PS algorithm to a stochastic method and applied it to the layout problem.

In the Extended Pattern Search layout algorithm, the order of component selection is randomized and each component is moved through a translation pattern until improvement is found. The same is repeated for each component for the rotation patterns. If at the end of this process no improvement is found, one or more components are swapped, assuming that they may improve the objective function. The step size is reduced and the process iterates through again, until a minimum step size is reached. Occasionally throughout the algorithm, the step size is increased based on the algorithm's progression and performance.

The randomization of component ordering, the judicious use of the swapping move, and the occasional step jumps all create a stochastic algorithm able to jump out of local, inferior optima. Details can be found in Yin and Cagan [1].

3 Octree Representation for Shapeable Components

Overlap between components is allowed and penalized during the layout since the presence of overlap is found to be essential for obtaining good solutions to the layout problem (De Bont et al. [5]). The exact interference calculation is time consuming when components are of complex geometry and in close proximity, typical for mechanical devices.

Within the EPS algorithm, an octree representation is used to model components of complex shapes and to evaluate interference between components. The octree-based interference detection is much simpler than the exact overlap evaluation. Multi-resolution octrees (Kolli et al., [6]; Cagan et al., [7]) are used in the layout
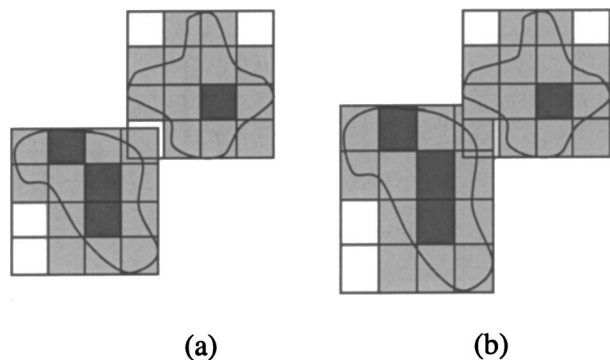

Fig. 1 Shapeable Component Quadtree Representations: (*a*) No Interference before Scaling; (*b*) Interference after Scaling.

for interference evaluation with different levels of accuracy; the resolution level is increased as the algorithm progresses.

A shapeable octree representation is introduced to evaluate the amount of interference between shapeable components. Shapeable components with base geometry of any default size can be imported from commercially available CAD packages. Octrees are generated from components of the base geometry. Each octree has a local coordinate frame attached to it. By keeping track of the movement of coordinate frames and mapping one to the other, we can perform interference analysis of components under translation and rotation moves in much the same way as done with fixed-size

(a)

(b)
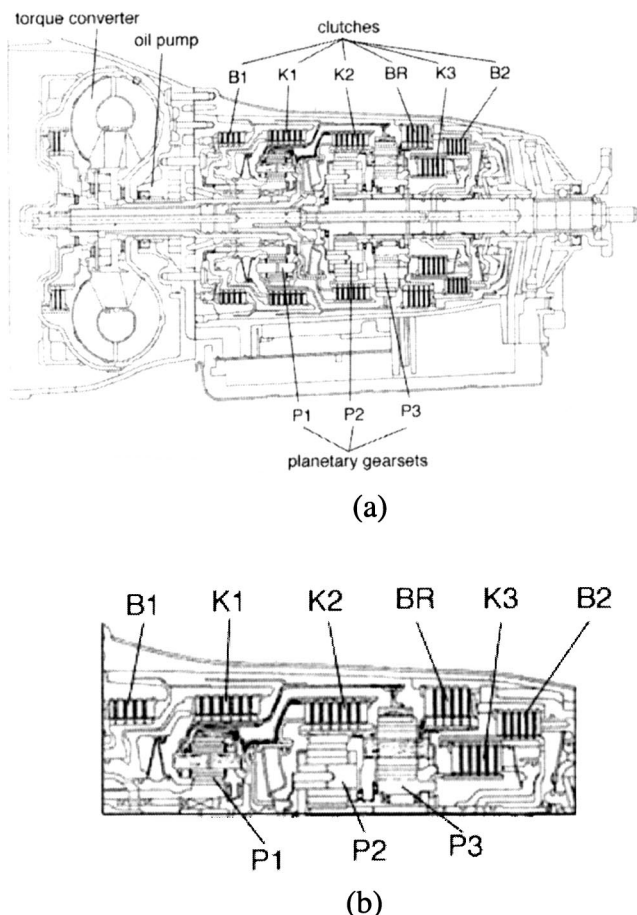
Fig. 2 An Automatic Transmission Assembly: (*a*) The Cross-Section View; (*b*) The Layout Space and Components.
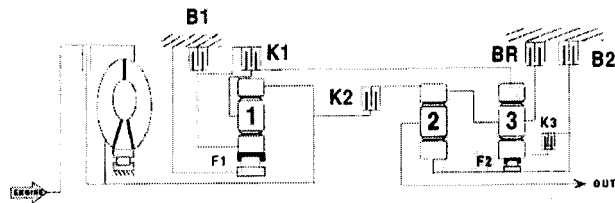
Fig. 3 A Stick Diagram of Component Connections in a Transmission

octrees. A 3-D vector is associated with each octree model to provide the scaling along local axes for shapeable components. The algorithm resizes a shapeable component whenever it is moved and provides the updated scaling factor for the interference analysis.

Figure 1 illustrates the shapeable component representation and the interference calculation process using quadtree models (the 2-D equivalent of 3-D octrees). In Fig. 1*a* the components are represented with quadtree models of level 2 using the default sizes and there is no overlap detected. In Fig. 1*b* one of the components is resized and overlap is detected between the partially full (gray) quadrants of the components.

In the EPS algorithm, after every component move, the sizes of shapeable components are adjusted and the starting and the ending points on routes are updated as necessary. The shapeable component representation can be used in layout applications where the parametric design of the components is necessary.

4 Automatic Transmission Design Example

The layout of the cross-section of an automatic transmission for a motor vehicle is a complex problem which involves the design and placement, in the cross-section, of many components including a system of clutches, and one or more planetary gear sets.

Automated cross-section layout tools remain unavailable for the *layout* of the cross-section of an automotive automatic transmission. Specialized tools have automated the development of stick diagrams to represent kinematics (Chatterjee and Tsai, [8]) or the imaging of planetary gear trains in 3D directly from the topological graph representation (Ramakrishnan and Olson, [9]), but none have addressed the automated placement of components within the transmission box.

Figure 2*a* illustrates the cross-section of a typical automatic transmission assembly and Fig. 2*b* shows the components and the container space used in the layout problem discussed in this paper. Only half of the cross-section needs to be modeled because it is axially symmetric.

Of the components included in the layout, planetary gear sets are considered to have pre-defined shapes and sizes that do not change during the layout. Multiple-disc clutches, however, are shapeable components whose sizes are related to their positions in the assembly and are to be determined during the layout.

The number of frictional discs and the size of the discs in a clutch are determined by the torque capacity, thermal capacity, and gain requirements, and they are related to the location of a clutch in the transmission assembly. The design requirements have to be checked and the clutch sizes adjusted accordingly during the layout process. The design considerations for clutches are from industry transmission design practices and can be found in Yin [10].

5 Problem Formulation

The transmission layout problem is formulated as a multi-objective optimization problem. The goal is to find a suitable sizing and placement of the components and the shell connections between them that satisfy functional requirements and achieve a compact package.
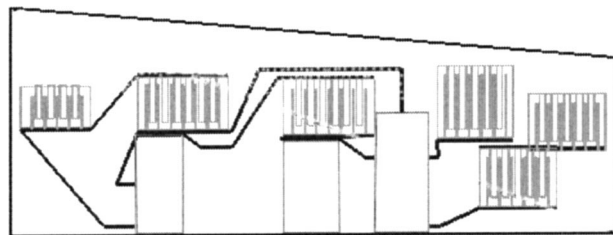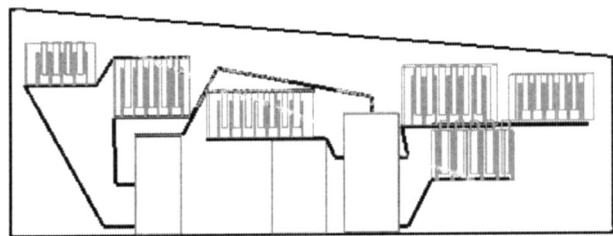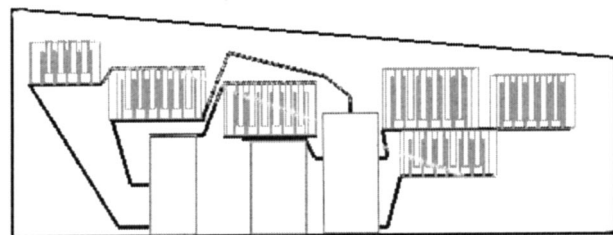
Fig. 4 The Original Transmission Layout–A Simplified Representation

(a)

(b)

Fig. 5 Two Solutions to the Transmission Layout Problem

The design variables include positions of components, locations of intermediate points on the shell connections, and sizes of shapeable components–the clutches.

The objective function is formulated as a weighted sum of individual goals:

$$\text{Minimize} \quad f = w_1 f_{placement} + w_2 f_{routing} + w_3 f_{penalty} . \quad (1)$$

The placement objective $f_{placement}$ is composed of attraction terms for components to stay inside the container, penalty terms for container protrusion and component overlap, and the bounding-box area as an indication of the compactness of the packing. The routing objective $f_{routing}$ consists of routing costs in terms of the shell connection length and the number of bends, and also a penalty term for the number of crossings between different shells. The penalty objective $f_{penalty}$ specifies constraint violations and thus drives the design into feasible ranges as the algorithm progresses. As presented in Szykman and Cagan [11], a penalty approach instead of a constraint propagation approach is taken since invalid designs with overlap and constraint violations are allowed during the optimization for a better exploration of the design space. The objective function is evaluated after each exploratory move and the resizing of shapeable components.

A simplified clutch representation is used in the layout here, but the shapeable octree can handle more complex geometries as more detailed representations are used downstream.

Topological connections between components are defined in a stick diagram, for this example shown in Fig. 3. Figure 4 trans-

Table 1 Comparing the Newly Generated Layouts with the Actual Design

# of Discs	K1	K2	K3	B1	B2	BR	OBJECTIVE
Figure 4	6	6	5	4	5	5	280.9
Figure 5(a)	5	7	5	4	5	6	240.7
Figure 5(b)	6	6	6	4	5	6	228.1

lates the original layout (Fig. 2b) into a simplified representation appropriate for conceptual layout design using our clutch and routing models.

6 Results

The automated layout tool using the EPS algorithm and a shapeable octree representation is coded in C++ and runs on major UNIX and PC platforms. The algorithm was run multiple times with consistent objective function values; each run takes an average of 5 seconds on a Silicon Graphics Indigo2 (195MHz, MIPS R10000 CPU, 128MB RAM). Two alternative solutions to the transmission layout problem (Fig. 4) are shown in Fig. 5. The solutions demonstrate similar configurations to the actual layout but with somewhat different positions and sizes for the clutches.

Table 1 summarizes the number of discs chosen for the six clutches in the actual and the newly generated layouts and compares their objective function values. As well, disk radii are sized dynamically as they are moved during layout optimization. The two alternative solutions are effective designs since the objectives are minimized, clutches properly sized, and routing restrictions from Fig. 3 are satisfied. The two newly generated solutions are better than the actual design *according to our problem formulation* as indicated by the objective function values shown in Table 1, although the design objectives used by the original designers are unknown.

7 Conclusions

The extended pattern search layout technique combined with the shapeable octree representation provides an effective tool for the automatic transmission layout and other design where components must be dynamically sized. Although the example used only two dimensions, the method is applicable for general 3D design. Future work on the transmission layout problem includes using the actual clutch geometry with exact piston and spring designs instead of the simplified models.

Acknowledgments

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Optimal Mechanism Design for Path Generation and Motions With Reduced Harmonic Content

Zhongfan Yuan

Professor, Ph.D., Mechanical Department, Sichuan University, Chengdu, Sichuan, 610065, P.R. China
e-mail: zfyuan5026@hotmail.com

M. J. Gilmartin

Reader in Engineering, Ph.D., School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, United Kingdom
e-mail: m.j.gilmartin@livjm.ac.uk

S. S. Douglas

Senior Lecturer, Ph.D., School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool L3 3AF, United Kingdom

The optimal design of linkage mechanisms for path generation and motions with reduced harmonic content is investigated in this paper. The designs are carried out using a two-objective optimizer based on fuzzy theory. The four-bar mechanism is first optimally designed to follow a specified coupler path with the harmonic content of the output link motion being simultaneously minimized to reduce its oscillating frequency bandwidth. For more complicated paths, a five-bar hybrid mechanism driven by a constant speed motor and a servo motor is also optimally designed. The harmonics in the servo motion are also reduced in the design to improve the dynamic characteristics for the servo motor. [DOI: 10.1115/1.1637661]

1 Introduction

In the process of optimal design of linkage mechanisms for path generation, harmonics reduction should be included. A literature review of applications of mechanism synthesis with harmonic motion reduction has been carried out by Connor et al. (1998) [1]. The results show the usefulness of harmonic information in the synthesis of mechanisms and the improved dynamic performance that can be achieved if the amplitudes of the motion harmonics are reduced. It is well known that if particular harmonics in exciting forces are close to a natural frequency in a machine, severe vibra-

tions will occur, such as the effect of servo motor torque harmonics on vibrational behavior. In this paper, an optimization method based on fuzzy theory which uses two objective functions is introduced. The objective functions are for minimum errors in following a required path and with reduced harmonic amplitudes in certain motions. Two design cases are considered. Firstly, a four-bar mechanism is optimally designed to produce a required coupler path with the harmonic content of the output link motion being simultaneously reduced. Secondly, a five-bar hybrid mechanism, driven by a constant speed motor and a servo motor, is optimally designed to produce a more complicated path. At the same time, the amplitudes of the harmonics in the servo motion are reduced. With this harmonic reduction, the servo motor frequency bandwidth needed to drive the servo link of the mechanism is reduced leading to improved servo motor performance.

The harmonic reduction method used here is different from others (Connor et al., 1998) [1] in that the reduction is carried out in the frequency domain. The discrete Fourier transform (DFT) is used to transfer the motion profile from the time domain to the frequency domain. Implementation computationally is carried out using the fast Fourier transform (FFT) algorithm. The fundamental harmonic occurs with a frequency equal to the cycle frequency of the mechanism. Reduction of the amplitudes of the higher harmonics is achieved by evaluating the second harmonic at each optimization interaction. It is observed that optimally reducing the amplitude of the second harmonic generally leads to a reduction in the higher harmonics also.

Fuzzy theory has been shown to be useful for engineering optimal design where inexactitudes in the design variables are the norm. Rao (1987) [2] used a fuzzy-based optimization technique to design a four-bar function generation mechanism. Krishna et al. (1994) [3] applied fuzzy set theory to design a four-bar linkage and a spatial mechanism for path generation. In the method, the design variables are referred to as a fuzzy set. Membership functions, which define boundaries for each optimization objective, are used to obtain the optimal results. Mechanism and optimization have also been addressed in some literatures [4–10]. In this paper, the fuzzy method is used as an optimizer using two objective functions which are based on accurate path generation and harmonic motion reduction. Fuzzy membership is used to find weighting coefficients heuristically for each objective. This is done by first optimizing each objective separately. The two objectives are then conjugated together using the determined weighting coefficients enabling a single objective optimization method to be employed. When the weighting coefficients have been heuristically determined, one of them can be varied during the optimization process to improve the common optimum for the two objective functions. A feature of this method is that only at the stage where the weighting coefficients are heuristically determined, i.e., when optimizing with single objective functions, need the constraint conditions be considered. At the second stage, when optimizing with the conjugated objective, the constraints can be ignored. A comparison of the method with a hierarchical optimization method is also carried out. Results indicate that the proposed method is more efficient than the hierarchical approach for the cases considered.

2 Fuzzy Weighting Coefficients With Two Objective Functions

As in the hierarchical optimization method, only one objective function $f_1(x)$, is first optimized while the second objective function $f_2(x)$ is ignored. The optimization is carried out taking into account the constraints and using standard methods such as a random search and variable metric combination. The optimal value, referred to as the ideal value for this objective function, is represented by $f_1^{\min}(x_1^*)$ and the design parameters contained in vector x_1^* are referred to as a fuzzy set. This set is then substituted into the second objective function $f_2(x)$, to obtain $f_2^{\max}(x_1^*)$. The sec-