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Design of Heat-Activated Reversible Integral Attachments for Product-Embedded Disassembly

Ying Li, Kazuhiro Saitou* and Noboru Kikuchi
Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109-2125

Abstract – Disassembly is a fundamental process needed for component reuse and material recycling in all assembled products. Integral attachments, also known as "snap" fits, are favored fastening means in design for assembly (DFA) methodologies, but not necessarily a favored choice for design for disassembly. In this paper, design methods of a new class of integral attachments are proposed, where the snapped joints can be disengaged by the application of localized heat sources. The design problem of reversible integral attachments is posed as the design of compliant mechanisms actuated with localized thermal expansion of materials. Topology optimization technique is utilized to obtain conceptual layout of snap-fit mechanisms that realizes a desired deformation of snapped features for joint release. Two design approaches are attempted and design results of each approach are presented, where the geometrical configuration extracted from optimal topologies are simplified to enhance the manufacturability for the conventional injection molding technologies. To maximize the magnitude of deformation, a design scheme has been proposed to include boundary conditions as design variables. Final designs are verified using commercial software for finite element analysis.

***Keywords*: design for disassembly, snap-fit joints, compliant mechanisms, thermal actuators, topology optimization**

1. Introduction

Driven by increasing social pressure to heighten environmental consciousness, design for disassembly has become one of the most significant challenges in the modern product design process. This is especially true in the consumer electronics industry due to high production volumes and characteristically short time scales of technological obsolescence. A novel and effective way to enhance the disassemblability of products is to embed a desired disassembly process in the products when they are manufactured [21, 5, 33].

Integral snap-fit attachments [30, 31, 16, 8] have been widely used as substitutes for separate fasteners for the purpose of design for assembly (DFA) [3, 22]. However, snap fits are not necessarily a favored choice for design for disassembly since they are often difficult to disengage without inherent destruction of the components [17]. While some snap-fits are designed to be reversible (*e.g.*, battery covers for cellular phones), auxiliary forces in a direction different from the insertion direction are usually required in order to unlatch the snapping features. The application of this disengaging force can be a problematic process. For instance, the location where the force is applied needs to be physically accessible. If an integral snap-fit is inside a mechanical system surrounded by other components, it can be disassembled only after the disassembly exposes the location to apply force. Furthermore, the auxiliary force can interfere with removal force, which is usually at a different location and in a different direction.

The motivation of this work is to develop an enabling technology for product-embedded disassembly by designing a new class of reversible integral attachments (RIA) that can be detached by the application of localized heat. According to [8], a snap-fit mechanism is composed of two functional units: a deflection mechanism and a retention mechanism. The proposed design methods utilize thermal expansion of materials to induce the deformation of deflection mechanisms (latch), thereby releasing the engaging joints (catch), and require no special materials or manufacturing technologies. An advantage of heat activation is that it can be applied through heat conduction in materials, such that the physical accessibility of the application location is not necessarily required. The interference to the removal force is also desirably avoided.

Two approaches are attempted in this work. One approach involves both engaging components of the snap-fit mechanisms, making use of thermal expansion of one component to indirectly apply force to the deflection mechanisms in the other component and

*Corresponding author:
Tel: +1-734-763-3875
Fax: +1-734-647-3170
Homepage: http://www-personal.engin.umich.edu/~kazu/
E-mail: kazu@umich.edu

cause favorable deformation to disengaging the locking. The second approach proposes to directly heat the deflection mechanisms at a certain location to cause disengagement by thermally induced deformation. It will be shown that these two approaches are proposed according to each individual design considerations and have their unique advantages. This work demonstrates the results from topology optimization techniques can be used to inspire the design layout and optimal geometrical configuration are extracted and simplified to enhance manufacturability. The simplified designs are then verified through finite element thermal-mechanical analysis using commercial software ABAQUS. Finally, in order to improve the problem of relative small deformation, a design scheme with variable boundary conditions has been proposed. In this improved approach, heat sink is considered along with heat source to increase the temperature differences as needed. The location of heat sink and heat source are optimized as discrete variables using genetic algorithm. The obtained result shows a dramatic improvement of performance.

2. Background

2.1. Design for product embedded disassembly

Academic investigations into the concept of "design for disassembly" began in the late 1980s, largely driven by successes with "design for assembly" earlier in the decade. Unfortunately, many guidelines suggested by the "design for assembly" methodology do not apply to "design for disassembly," for instance [17, 14, 13, 9]:

- Rapid attachment fasteners employed in assembly may not be suitable for disassembly. For example, glue can be used to easily join two plastic parts, but the resulting joints cannot be detached without damaging both parts.
- Products designed for assembly may not allow easy access to the specific components to be recovered. For example, a product may require the removal of *100* components to reach *one* component with high recycling value. In such cases, disassembly may not be economically feasible.
- The condition of products at disassembly may be different from the conditions under which the products were initially assembled. For example, wear or corrosion may make bolted joints extremely hard to detach.
- Due to the significant spatial and temporal distance between the assembly and disassembly processes, it may not be immediately obvious how to disassemble a part.
- Parts that appear similar may require completely different approaches to disassembly.

Efforts to overcome these disassembly obstacles through the concept of "*product-embedded disassembly*" or "*self-disassembly*" have recently started appearing in the literature. Product-embedded disassembly gives a product the ability to take itself apart. Chiodo *et al.* [5] demonstrated the feasibility of a self-disassembly strategy for consumer electronic products using fastener screws made of shape memory polymers. Masui *et al.* [21] demonstrated the self-disassembly of a CRT using nichrome wire embedded in the component glass along the desired boundary for separation. Although these examples were effective in the particular cases presented, both methods lack generality since they require the use of specialized and costly materials such as shape memory polymers.

2.2. Design of compliant mechanisms

Since the deflection mechanism part of a snap-fit is basically structural component, which functions by elastic deformation during engagement or disengagement of the locking, it can be recognized as a special case of compliant mechanisms. A compliant mechanism is the type of mechanism that relies on the deflection of flexible members to transfer motion, force or energy. Design methods of compliant mechanisms have been studied by many researchers [11]. While most of simple-geometry compliant mechanisms are derived from their conventional counterpart, in this work we have attempted to accredit a specific design approach, topology optimization, as inspirational tool to enlighten the possibility of a more systematic design scheme in the future. Even though the purpose of this paper is to introduce new designs of snap-fits, for completeness of the presentation topology optimization for compliant mechanisms is reviewed in this section[1]. Topology optimization based on homogenization design method [2] is a continuum synthesis approach of designing compliant mechanisms [1, 26, 23, 7]. Thermal actuation has attracted quite much attentions in compliant mechanism designs for many advantages [27, 32, 19].

There are two basic design requirements for compliant mechanisms: flexibility and stiffness. To transfer motion with elastic deformation, complaint mechanisms are required to favorably deform in order to provide output displacement in desired directions. This requirement is measured by the concept of mutual mean compliance (MMC) [24, 12] in linear elasticity theory. In order to transfer force and resist reactive force, a compliance mechanism needs to have strength under forces in certain directions. This requirement is measured by mean compliance (MC). These measures are mathematically formulated as energies based on the principle of virtual work [23]. Fig. 1 shows the three loading cases that are

[1]For detailed technical description of topology optimization techniques used in this work, interested reader should refer to other publications by the authors.

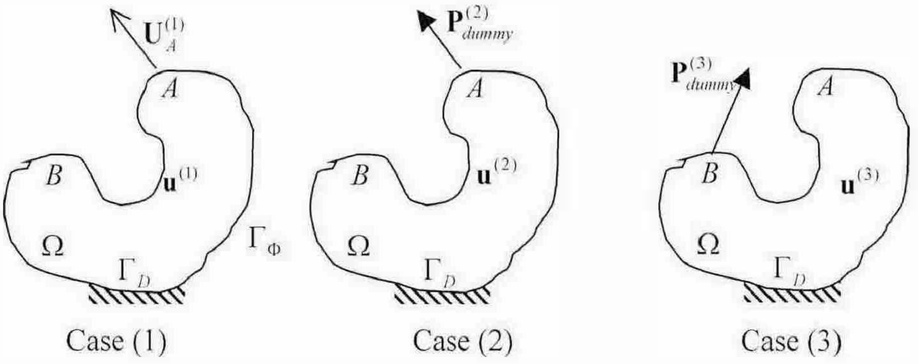


Fig. 1. Loading cases considered for design criteria.

considered for these energy formulations. Among these, the first loading case represents the loading methods. For conventional mechanisms, an input force is applied and generates displacement fields $\mathbf{u}^{(1)}$. In the design of thermally actuated compliant mechanisms, displacement field is caused by a temperature change $V\Phi$, which can be achieved by either a uniform heating or a time-transient heating effect. The dummy load in second loading case is combined with first loading case to formulate MMC, and the dummy load in third loading case ensures the stiffness of the mechanism. Mathematically, MMC and MC can be expressed as:

$$
\begin{aligned}
MMC &= a(\mathbf{u}^{(1)}, \mathbf{u}^{(2)}) = \int_{\Omega} \mathbf{e}^{T}(\mathbf{u}^{(1)}) \cdot \mathbf{s}^{(2)} d\Omega \\
&= \int_{\Omega} \mathbf{e}^{T}(\mathbf{u}^{(1)}) : \mathbf{C}^{H} : \mathbf{e}(\mathbf{u}^{(2)}) d\Omega \qquad (1) \\
MC &= a(\mathbf{u}^{(3)}, \mathbf{u}^{(3)}) = \int_{\Omega} \mathbf{e}^{T}(\mathbf{u}^{(3)}) : \mathbf{C}^{H} : \mathbf{e}(\mathbf{u}^{(3)}) d\Omega
\end{aligned}
$$

where $\mathbf{u}^{(i)}$, $i=1, 2, 3$ are the displacement fields in the three loading cases illustrated in Fig. 1, $\mathbf{e}$ and $\mathbf{s}$ are the corresponding strain and stress tensors, and $\mathbf{C}^{H}$ is fourth order tensor of homogenized material constants. Ω denotes the extended design domain and $a(,)$ represents the bilinear operator.

The topology optimization problem is formulated as a problem of finding the optimal distribution of material properties in an extended fixed domain Ω where some structural cost function is minimized. The design variables are the values of some density characteristic function δ over Ω. Both requirements of flexibility and stiffness are formulated into the topology optimization problem as a multi-objective function. The multi-objective function is formulated as:

$$
\max_{\delta} \; f = \frac{a(\mathbf{u}^{(1)}, \mathbf{u}^{(2)})}{a(\mathbf{u}^{(3)}, \mathbf{u}^{(3)})}
$$

Subject to:

$$
\text{(a)} \quad a(\mathbf{u}^{(i)}, \mathbf{u}^{(i)}) = \int_{\Omega} \mathbf{f}^{(i)} \cdot \mathbf{u}^{(i)} d\Omega, \; i=1, 2, 3 \qquad (2)
$$

$$
\text{(b)} \quad V = \int_{\Omega} (1-\delta^{3}) d\Omega \leq \overline{V}
$$

$$
\text{(c)} \quad 0 \leq \delta \leq \overline{\delta} < 1
$$

where (a) represents the equilibrium equations for the three loading cases, (b) is the volume constraint and (c) is the bounds for design variables. In solving the problem, the extended design domain is discretized with finite elements and evaluation procedure is composed of linear static mechanical analysis, which does not require particular input values of loading conditions in such an optimization problem. This homogenization method based topology optimization technique has been proved successful to design continuum type of compliant mechanisms. In this work this method is further utilized to conceptually design components of snap-fits mechanisms.

3. Approach I: Two-component Design

3.1. Motivation

In a previous effort of producing environmental conscious (ECO) designs, a heat-activated snap-fit mechanism made of recyclable materials [18] had been designed, in which specially designed composite material (material with negative thermal expansion coefficient) was used to induce a desired deformation from a global temperature change of the structure. However, if only traditional materials, i.e., materials with positive thermal expansion coefficient, are to be used for this type of application, a uniform temperature increase does not guarantee an appropriate mechanism function. Furthermore, unnecessary heating may cause problems during operation. For example, a uniform temperature change is not trivial to obtain considering the various environmental and operational conditions. Another challenge could be that the increase of temperature may cause unwanted heating to neighboring components, which may even cause damages. A solution can be the utilization of *local* heating to generate *partial* thermal expansion of the mechanism.

Due to heat conduction in materials, localized heating is limited to a certain time period. The topological design techniques for compliant mechanisms can be expected to take temperature change or force as actuation. The first approach is to separately design the component to be heated and the component that needs to deform (deflection mechanism). To conceptualize design

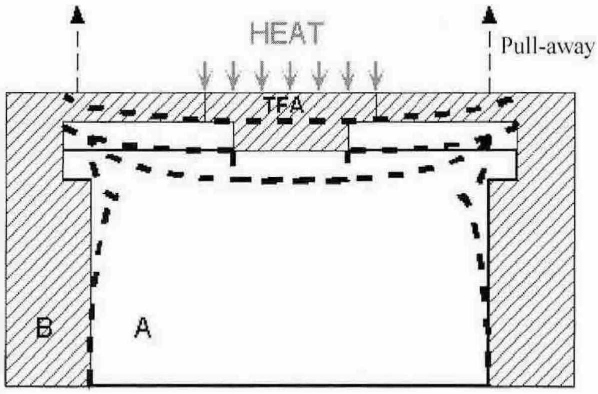


Fig. 2. Illustration of Two-component design.

specification, a localized heating can be approximated by a uniform temperature change in a local portion of the mechanism. Since thermal stress can generate significantly large output force, when two component physically contact with each other, the output generative force of the heated part becomes the input force to the deflection unit. This design idea is illustrated in Fig. 2. A and B are the two components which are locked through snap-fit locking. The so-called thermal force applicator (TFA) is the heated part of B, which provides an input force to the deflection unit (in A) and cause the disengagement of locking (deformation shown as by dash lines). Since high temperature distribution is expected to be concentrated in TFA, the heating is approximated to be uniform temperature change in TFA.

3.2. Design of TFA and deflection mechanisms

TFA needs to be designed to maximize the output force and part A needs to be designed to deformed in the desirable manner as shown in Fig. 1. Therefore two separate topology optimization problem need to be solved. Each problem is formulated according to these requirements.

Design of TFA is to find optimal layout in the design domain (Fig. 3(a)), to achieve maximum output force at the top in the vertical direction when the whole material is heated uniformly. Due to symmetry of the mechanism, half of the design domain is considered. In designing actuator type of compliant mechanisms or actuators, the required stiffness is in the opposite direction of required displacement. The optimization problem is formulated as in Eqn. (2) with the uniform temperature change in solving Eqn. (2a) when $i=1$ [18], the optimal configuration is obtained as shown in Fig. 3(b). In order to enhance manufacturability, simplification scheme is applied to the optimal configurations. Since the major manufacturing processes considered here is the economic injection molding, the simplifications have been conducted by removing materials which may cause internal cavities and re-shaping of structural members to avoid negative angles in molding. Accordingly, the geometry result has been extracted as in Fig. 3(c).

In designing deflection mechanism, besides the disengagement deformation under input force, there is also a stiffness requirement such that the mechanisms provide maximum retention force. The design domain with these design criteria is shown in Fig. 4(a). Optimal layout is found using problem formulation for compliant mechanism [23] in Fig. 4(b) and the extracted geometry result is shown in Fig. 4(c).

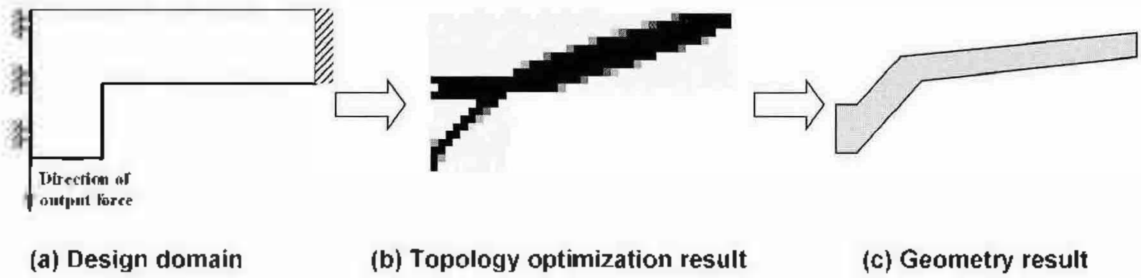


Fig. 3. Topology optimization for TFA.

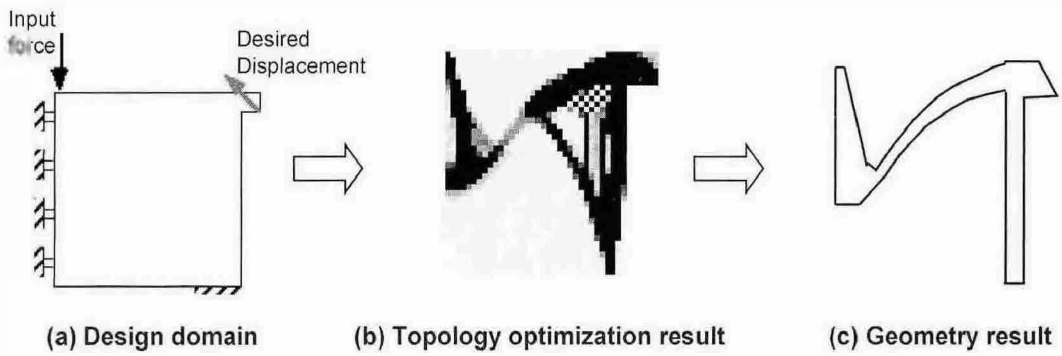
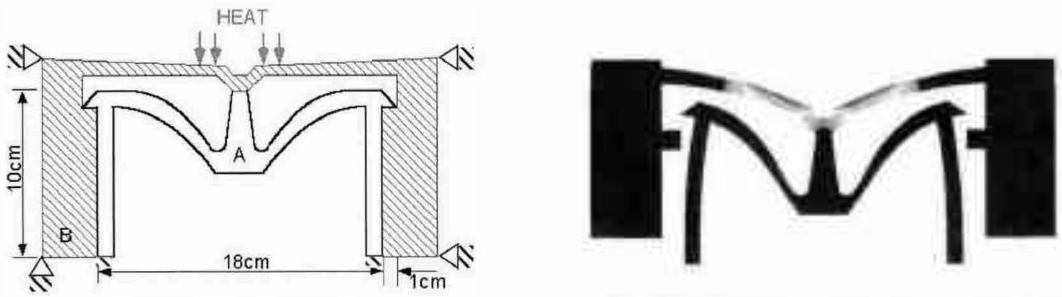


Fig. 4. Topology optimization of deflection unit.



(a) Integrated design

(b)Verification with time transient analysis

Fig. 5. Result of Two-component design.

3.3. Design verification

In Fig. 5(a), TFA and snapping mechanisms are integrated together to illustrate the final design. Even though uniform temperature change was assumed while TFA is designed, it can approximate the effect of local heating during a limited heating time. Boundary heating and heat conduction in the materials is more realistic in real applications. Therefore, the verification of the design is conducted using time transient analysis. It is done by a time transient heat transfer simulation followed by a thermal-stress analysis with commercial software ABAQUS. This procedure is called a sequential thermal-mechanical analysis in finite element simulation [10]. The deformed plot along with temperature distribution contour plot is shown as Fig. 5(b). (Note: the geometry of the engagement has been modified in FEM simulation to avoid the usage of contact elements.)

In this verification, material properties are chosen as be close to those of a common thermal plastic material Polypropylene: density ρ=930 kg/m^3, thermal conductivity λ=0.22 J$\cdot$(smK)$^{-1}$, specific heat c = 1.9 E3J$\cdot$(kg$\cdot K)^{-1}$, Young's modulus E=1.1 GPa at room temperature 20°C and E=0.2 GPa at 120°C, Poison's ratio ν=0.45, thermal expansion coefficient α=8.0E−5$(K)^{-1}$. Values of E between the 20°C and 120°C are simulated using an exponential function and the temperature dependency of the rest of material properties are ignored.

Initial temperature is set to be 20°C and the heating condition is fixed temperature of 100°C at the heated location (shown in Fig. 5(a)), which is below the heat distortion temperature. The size of the snap fit is about 10 cm in height, the heating time is about 300 seconds. The inward deflection at the tip of hangover is approximately 1 mm. However, in order to generate a clear demonstration of the deformation, the deflection is magnified by a factor of 10 in Fig. 5(b). In other words, in real design the size of the locking feature needs to be scaled down. This small deflection is because of the limits of thermal expansion coefficient a regular material has. Since the deflection is quite small, it requires relatively large snap-fit size. Further investigation is needed to reduce the overall size of snap-fit while achieving similar amount of deflection. Future work is proposed in the last section of this paper.

4. Approach II: Single-Component Approach

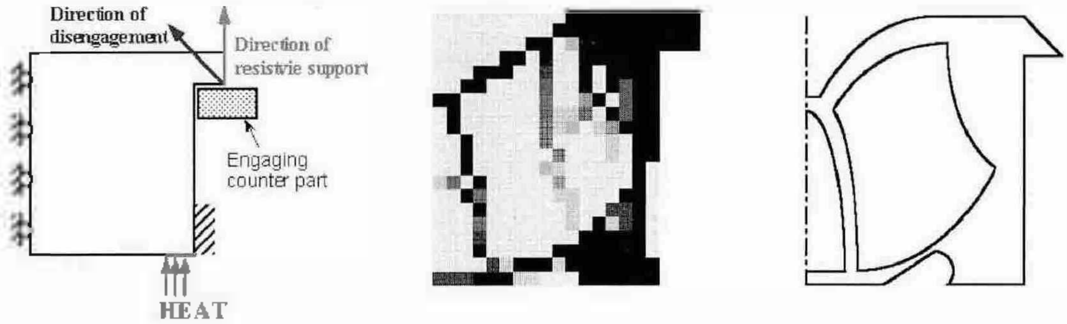
4.1. Motivation

As discussed in the previous section, including time transient effect of heat transfer is more realistic in practical design problems. It is desirable to include this consideration into the conceptual design stage. In other words, temperature gradient can be taken into account in the topology optimization process and design material layout that can conduct heat in a favorable way, as well as cause deflection in the preferred manner. Accordingly, topology optimization technique taking benefit of non-uniform temperature distribution has been developed. One example is design of the so-called "electro-thermal-compliant" (ETC) micro-actuators [32], in which the non-uniform joule heating was generated through non-uniform electric current. For the application of macro-scale and simple heat source, topology optimization technique considering time transient effect of heat transfer has been proposed and developed[2]. In this case, non-uniform temperature distribution is caused by time transient effect of heat conduction. For a snap-fit mechanism, designing the deflection unit to be heated during a certain period of time and deforms to disengage from the counter part can realize the idea of product-embedded disassembly. Since the only part that needs to be designed is the deflection unit using this technique, we refer to it as the single-component approach.

4.2. Design of heated deflection mechanisms

In designing the transient effect in deflection mechanisms, the topology optimization problem is formulated to find the optimal material distribution in the extended design domain (Fig. 6(a)) to conduct heat and cause deformation in favor of disengagement of locking. The multi-objective optimization problem is

[2]For details on problem formulation considering time transient effect, refer to [19].



(a) Design Domain (b) Topology optimization result (c) Extracted optimun layoyt

Fig. 6. Design domain and result.

formulated similar as in Eqn. (2). However, in this optimization problem, the displacement field of first loading case (Fig. 1) is caused by a transient temperature distribution at a actuation time. Design domain along with boundary condition and design requirements are shown in Fig. 6(a). The optimization procedure comprises of 1) an evaluation process, which is a finite element simulation of time transient heat transfer and thermal-mechanical analysis, 2) a sensitivity analysis of both thermal and mechanical responses and 3) a sequential linear programming (SLP) optimization algorithms.

Topology optimization result of the design domain is shown in Fig. 6(b). Although there are some intermediate density values visible in the result, the basic layout can be extracted (shown in Fig. 6(c)) and easily understood by engineering judgment. When external heating is applied, the outer region expands vertically more than the inner region, which causes the hangover part to be lifted in the upper and inner direction. At the same time, the expansion of lower horizontal oriented member further pull the inner region members to move downward, which helps the mechanism to deform in a more favorable manner. The triangular shape structure in the center provides large stiffness while the material volume is limited.

4.3. Simplification and verification

The extracted two-dimensional design is verified using ABAQUS simulation. Deformed shape and temperature distribution are shown in Fig. 7. After the deformation pattern is verified, more adjustment can be applied to the design in order to enhance manufacturability. Since the final 2D geometry contains internal holes, it would be difficult to be injection molded. To overcome this difficulty, further simplification is conducted and the

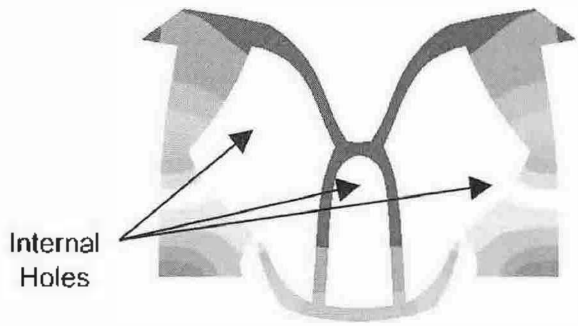
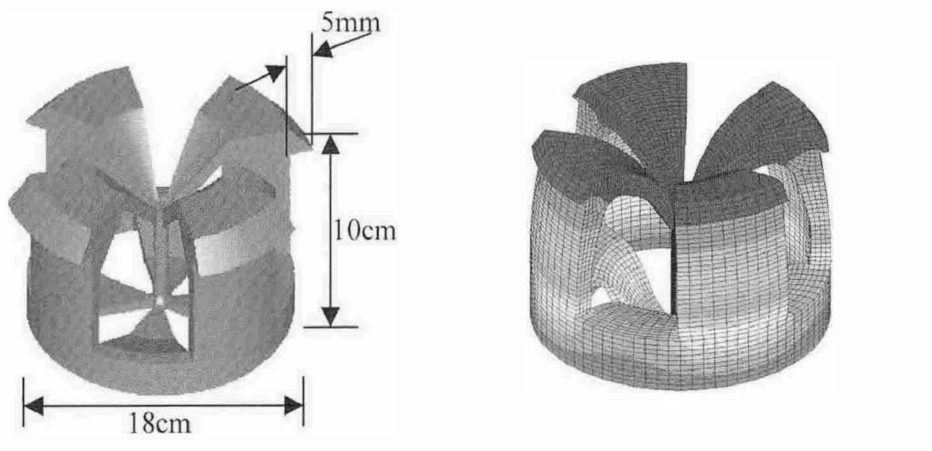
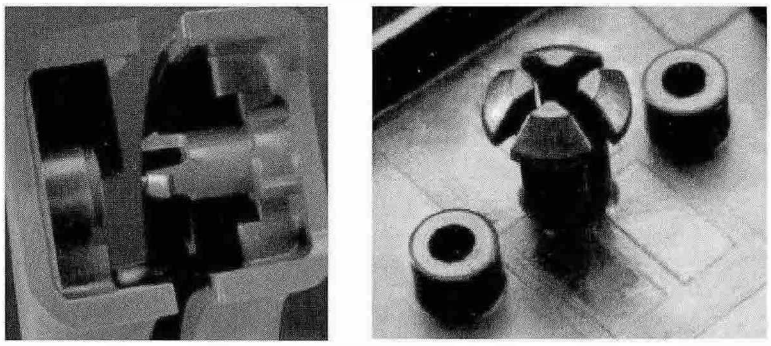


Fig. 7. ABAQUS verification of 2D result.



(a) 3D CAD model (b) ABAQUS Verification of deformation

Fig. 8. Realized 3D model and verification result.



(a) Saw Handle (b) Mirror patch cover

Fig. 9. Cylindrical cantilever type snap-fit mechanisms.

2D geometry can be swept axially into 3D to avoid internal holes. Fig. 8(a) shows a three-dimensional CAD model after the modification. Although the geometry is further simplified, the basic functioning members still remain and ABAQUS simulation verifies that the desirable deformation pattern can be achieved (Fig. 8(b)). In this verification, same material as described in section 3.3 is used. Similar dimensions are used for comparison of results from the two approaches. Actuation time is chosen as 500 seconds. The inward deflection at the tip of hangover is approximately 0.5 mm, which means in application, the hangover size should be about 0.5 mm in order to achieve disengagement. And the displayed deformation (Fig. 8(b)) is magnified with a factor of 20 for clear demonstration. Again, the achieved deflection is quite small compared with the overall size of the snap-fit. This is a big challenge to the proposed design method. In section 5, we propose several solutions to this problem.

In fact snap-fit mechanisms with similar geometry as the 3D moldable design have been widely used in practice. For instance, the cylindrical cantilever type of snap fits used to integrate saw handles and mirror patch covers (Fig. 9). These existing snap fits are usually difficult to disengage. If the mechanism presented in this paper is introduced, it could make a significant difference in product disassembly. Furthermore, since heat can applied through heat conduction in materials, this type mechanism can solve the disengagement problem of far-from-reachable integral attachments.

5. Design Scheme With Variable Boundary Conditions

As mentioned earlier, the thermal expansion induced deflection is very limited, due to the limitation on thermal expansion coefficient of regular materials (less than 1.0E-5 K^{-1}). According to the design verifications in this paper, the ratio of hangover size to snap-fit size is in the range of 0.005~0.01. Therefore this design concept is only applicable to those snap-fits of relative large size, fairly small locking features or tight mating tolerance. To further investigate this problem, we have attempted to relax the design specifications.

First, heat sink can be used, which means, while some portion is heated and expands, some other portion of the mechanism can be cooled and shrink. This effect is similar to increasing thermal expansion coefficient or applying higher temperature, therefore can help increase the deflection. Secondly the deformation can be sensitive to the location and intensity of heating and cooling, so that the boundary location where to put heat source and heat sink can be design variables rather than fixed boundary conditions.

To further refine the presented design approach, especially the single component approach, we propose a design scheme, which optimize not only the layout and topological features but also the specification of boundary and loading conditions. This has been realized by the decomposition of optimization procedure according to separate types of design variables: density variables and boundary variables. In other words, it is true that:

$$\min_{a,b} f(a,b) = \min_{b}[\min_{a} f(a,b)] \tag{3}$$

where a and b stand for the set of design variable associated with topology optimization and those of boundary and loading condition respectively. A similar design approach had been used to design optimal shape and location of piezoelectric materials in flextensional actuators [20].

As illustrated in Fig. 10, the optimization procedure consists of two layers of optimization, an inner loop of topology optimization (shown with line arrows) and an outer loop of optimization on boundary conditions (shown with block arrows). Since topology optimization techniques deal with finite element model, the design variables in the outer loop are discrete variables. Therefore, genetic algorithms has been used as the optimization algorithm the in the outer loop, while sequential linear programming is used in the inner loop. In this work, commercial software iSIGHT is used to integrate the two layers of optimization as well as implement genetic algorithm optimization.

Consider the design domain in Fig. 11(a), only half

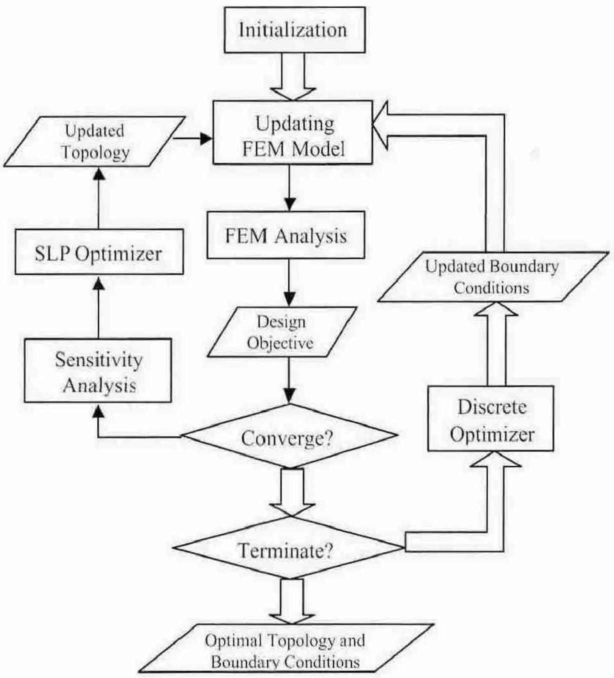


Fig. 10. Improved design scheme.

of the symmetric domain is shown for snap-fit design. Since the primary goal is to maximize the deformation, the only objective used in topology optimization and boundary optimization is the maximum displacement in the disengagement direction, i.e. maximum mutual compliance. The reason for this modification to previous objective function can avoid possible dominance of contribution by over-stiffness. To ensure the snap fit have necessary structural components, a non-design domain (shown in gray color) is pre-defined. During the new optimization process, topology design (the big question mark) is solved in the inner loop, which is similar to approach 2, and boundary or loading conditions (two small question marks) are solved in the outer loop. In this work, we used three design variables associated with the specification of boundary condition as shown in Fig. 11(a). Assuming the heat location start at the lower right corner of the design domain, the design variables are:

- The length of heated portion l_h
- The starting location of cooled portion n_c
- The length of the cooled portion l_c

Since they are incorporated in the finite element model, they all have discrete values. The following constraints have to be imposed on these variables to avoid boundary conflictions:

$$n_c > l_h$$

$$n_c + l_c < L_D$$

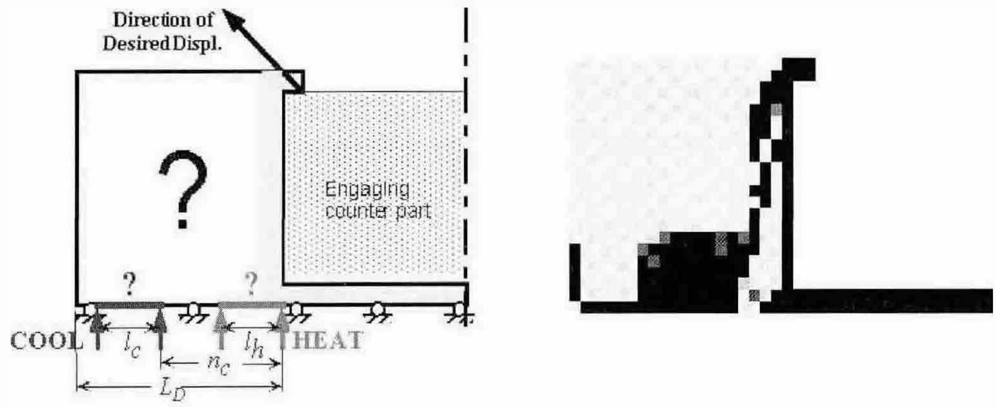
where L_D is the length of the design domain.

The heating temperature is 100°C as in previous examples and the cooling temperature is chosen to be -20°C. After the integrated topology-boundary optimization process, the optimal configuration has been found as in Fig. 11(b). The values of optimal boundary conditions are:

$$l_h = \frac{3}{20}L_D;\ n_c = \frac{9}{20}L_D;\ l_c = \frac{4}{20}L_D$$

Similar to previous sections, simplification is conducted to eliminate internal holes and excessive geometries as well as smoothen the shape of the structure. The final optimal design and optimal boundary condition is illustrated as in Fig. 12.

Verification result with ABAQUS is shown in Fig. 13 with a magnification factor of 2.5. With the same material properties as in previous examples, this design provides a deflection-to-height ratio of 0.025, which is a 150% increase to the designs in previous sections. (The expansion of the horizontal bar at the bottom contributes a 70% increase out of the 150%.) Even though this ratio is still less than ideal, it demonstrates a big



(a) Design Domain

(b) Optimal Configuration

Fig. 11. Design of topology and boundary conditions.

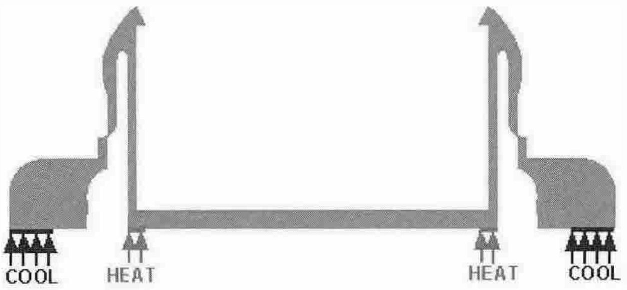


Fig. 12. Final design with specified conditions.

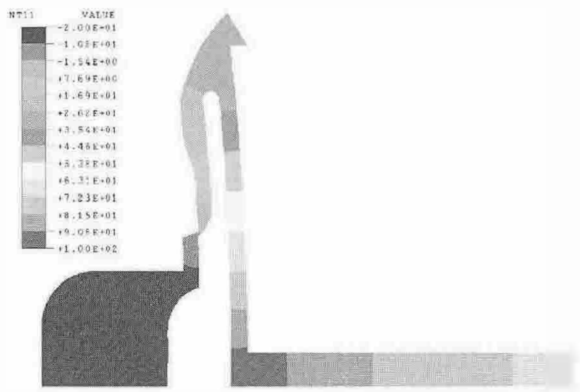


Fig. 13. Verification result of design with variable boundary conditions.

design improvement by giving more design freedoms.

6. Conclusions and Future work

In this paper, we proposed a method for design of a new class of reversible integral attachments mechanism, which is activated by localized heat. Two design approaches based on topology optimization technique for compliant mechanisms are proposed and individual design results are presented. Combining both approaches, design flexibilities can be provided while practical problem is encountered.

- Two-component approach separates the heated part and deflected unit, while the deflection unit is heated directly with single-component approach. This allows the designer to consider different material selections to each component and make good use of special material properties according to different needs.
- Heat source is applied externally to the snap-fit when disengagement is needed. Two-component design is heated from the top, while single-component design was heated from the bottom. Designers can choose to apply heat at the location that is easily accessible.

The designs in this paper represent our preliminary attempt towards the effective utilization of localized heat in the application of design for disassembly and serve as a promising start for further investigations.

First of all, the idea of shrink-fit [25] can be incorporated to overcome the problem of small deflection. If we considered the temperature change of surrounding areas of a snap-fit, the thermal expansion of the outer region can help adding up the gap between two locking components. This principle is very similar to that of shrink-fits assembly process, where one component (with a hole) is heated and expands to fit into another component (shaft). However, for typical shrink fit, the tolerance is extremely small, and disassembly is barely possible. Combining both snap-fit and shrink-fit features, a hybrid type of assembly mechanisms can be designed and inherit benefits from both features, such as the easy arrangement of snap-fit, high joint stiffness of shrink fit, and disengaged using localized heat.

Secondly, in this paper, only conduction is considered in the heat transfer analysis. Other heat transfer types such as convection and radiation are omitted because the less significant contributions to temperature change. For a more sophisticated design, their influences can be included into the design evaluation.

Thirdly, the obtained optimal designs in this paper are based on the criteria of self-disassembly and retention support. However, there are many other evaluation metrics [28] that should be considered into design criteria. These metrics can be mathematically formulated into the topology optimization problem. Engineering designs have always had multiple criteria. The optimization problem can reflect these design considerations by more carefully elaborated multi-objective function. For example the locking ration can be included into the optimization by using another mutual mean compliance term formulated between the loading cases of insertion force and dummy load in the direction of desired engagement deflection. In addition, the actuation time in this presented work has been chosen as to induce significant temperature gradient. It is generally determined by material thermal properties, intensity of heat source and environmental condition. A further study can also take actuation time as a design parameter for more preferable practice.

Thirdly, in the aspect of optimization methods, genetic algorithm (GA) based topology optimization techniques have been developed and improved to address variable boundary problem [4, 15, 29]. In a further work, GA can be implemented to substitute the two-layer optimization procedure.

Finally, engineering designs need refinements and justifications in shape and dimension according to individual applications. Optimization of control points [6] and control parameters, combined with FEA evaluation process, can be applied to further improve performance, reduce stress concentration, and achieve final optimal designs.

In summary, this paper proposes to apply the time-transient effect of heat transfer in attachment integral design. In other words, non-uniform temperature change and thermal expansion can be achieved within a certain time period while the mechanism is heated locally. It is expected that, with further study for improvement, the proposed design method can create a new class of snap-fits, which can be adopted in a wide range of products in order to realize the products with an embedded disassembly means for component reuse and material recycling.

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Ying Li graduated from Peking University with B.S. in Mechanics (1996). She received her M.S.E. (1997) and Ph.D. (2002) in Mechanical Engineering from University of Michigan-Ann Arbor. She is currently working in Advanced Analysis Department, American Bureau of Shipping. Her research and work interests are mechanical analysis and structural optimization.

Noboru Kikuchi received his B. Eng. From the Tokyo Institute of Technology in 1974 in Civil Engineering, MS and PhD from University of Texas at Austin in 1975 and 1977 in Engineering Mechanics, respectively. Since 1980, he has been with the Department of Mechanical Engineering at the University of Michigan, Ann Arbor, where he held positions of Assistant Professor (1980-1983), Associate Professor (1983-1985), Professor (1985-preseent), and Roger L. McCarthy Professor (2004-present). He serves as Chairman of the Board of Directors, the Japan Association for Nonlinear CAE [NPO] (2003-Present), Director of Toyota Central R&D Laboratory (2003-Present), Associate Technical Advisor, Production Division, Toyota Motor Corporation (2002-Present), Senior Fellow, Toyota Central R&D Laboratory (1999-2002). He is a recipient of numerous awards including the Henry Russel Award, the University of Michigan (1985), Distinguished Research Award, Engineering College, the University of Michigan (1991), the Best Paper Award, ASME Design and Automation Conference (1993), Computational Mechanics Achievements Award, the Japan Society of Mechanical Engineers (1999), Design and System Engineering Achievement Award, the Japan Society of Mechanical Engineers (2002). Dr. Kikuchi is a founding member and Fellow of US National Association for Computational Mechanics, Fellow of International Association for Computational Mechanics, and Senior Fellow of Japanese Society of Applied and Industrial Mathematics.

Kazuhiro Saitou received his B. Eng. with Honor from the University of Tokyo in 1990, MS and PhD from the Massachusetts Institute of Technology (MIT) in 1992 and 1996, respectively, all in mechanical engineering. During 1997 and 2003, he was an assistant professor in the Department of Mechanical Engineering at the University of Michigan, Ann Arbor, where he is currently an associate professor. His research interests include design automation and optimization, design for X, where X = manufacture, assembly, robustness, environment, etc., modeling and optimization of micro electro-mechanical systems, evolutionary computation in mechanical design. He is an editorial board member of *International Journal of CAD/CAM* and *Genetic Programming and Evolvable Machines*. He received the 1999 CAREER Award from the National Science Foundation. Dr. Saitou is a member of ASME, ASEE, IEEE, ISGEC, JSME, and Sigma Xi.

Ying Li

Kazuhiro Saitou

Noboru Kikuchi