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DESIGN FOR DISASSEMBLY WITH HIGH-STIFFNESS, HEAT-REVERSIBLE LOCATOR-SNAP SYSTEMS

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ABSTRACT

Recent legislative and social pressures have driven manufacturers to consider effective part reuse and material recycling at the end of product life at the design stage. One of the key considerations is to design and use joints that can disengage with minimum labor, part damage, and material contamination. This paper presents a unified method to design high-stiffness reversible locator-snap system that can disengage non-destructively with localized heat, and its application to external product enclosures of electrical appliances. The design problem is posed as an optimization problem to find the orientations, numbers, and locations of locators and snaps, and the number, locations and sizes of heating areas, which realize the release of snaps with minimum heating area and maximum stiffness, while satisfying any motion and structural requirements. Screw Theory is utilized to pre-calculate a set of feasible orientations of locators and snaps, which are examined during optimization. The optimization problem is solved using Multi Objective Genetic Algorithm (MOGA) coupled with structural and thermal FEA. The method is applied to two-piece enclosure of a DVD player with a T-shaped mating line. The resulting Pareto-optimal solutions exhibit alternative designs with different trade-offs between structural stiffness during snap engagement and area of heating for snap disengagement. Some results require the heating of two areas at the same time, demonstrating the idea of a lock-n-key.

INTRODUCTION

Recent legislative and social pressures have driven manufacturers to take responsibilities for reducing the amount of materials that end up in waste stream at product retirement. As such, products are now designed with increased emphasis on effective part reuse and material recycling at the end of product life using Design for Disassembly (DFD) [1-4] guidelines. One of the key considerations in DFD is the design and use of joints that can disengage with minimum labor, part damage, and material contamination.

Reversible snaps, often found at battery covers in electrical appliances (see Figure 1 for examples), are good candidates for such joints. They allow easy, non-destructive and clean detaching between mating parts at a desired time. However, these snaps are prone to accidental disengagement since they must sacrifice stiffness for the ease of disengagement, which is achieved by the displacement of locking surfaces by the auxiliary force on joint features such as tab, lever, and boss. Also, when used in external product enclosure, the aesthetic appeals of the product can be damaged due to the exposure of the joint features to which the unlocking force needs to be applied.

Figure 1. Battery covers of remote control units utilizing locators and reversible snaps.

Accordingly, the objective of this paper is to present a unified method for designing a high-stiffness, reversible locator-snap system that can be disengaged non-destructively with localized heat, and its application to the external product

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enclosures of electrical appliances. The proposed heat-reversible locator-snap system consists of locators and snaps molded on the internal surfaces around the mating line of a thin-walled enclosure part. While assembled, the locators and the snaps respectively engage with the protrusions and the catches molded on the mating part, thereby constraining their relative motions. During assembly, the elasticity of the thin-walled parts is exploited to enable the snapping action. During disassembly, in-plane thermal expansion constrained by locators and temperature gradient along the wall thickness are exploited to realize the out-of-plane bulging of the enclosure wall that releases the snaps.

The design problem of the high-stiffness, heat-reversible locator-snap system is posed as an optimization problem to find the orientations, numbers, and locations of locators and snaps, and the number, locations, and sizes of a heating area, which realize the release of snaps with minimum heating area and maximum stiffness while satisfying any motion and structural requirements. The Screw Theory is utilized to pre-calculate a set of feasible orientations of locators and snaps that are examined during optimization. The optimization problem is solved using multi-objective genetic algorithm coupled with structural and thermal FEA. The method is applied to two-piece enclosure of a DVD player with a T-shaped mating line. The resulting Pareto-optimal locator-snap systems exhibit snap disengagement with small heating area and sufficient stiffness to withstand its own weight. Some results require simultaneous heating of two areas, demonstrating the idea of a lock-n-key.

RELATED WORK

Analysis and Design of Snap Fits

Snap-fit is a preferred joining method for design for disassembly because it does not need of extra parts for joining, is easily assembled, and can be made cleanly separable, all of which contribute to the reduction of overall product cost and realization of economic recycling processes [5,6,7]. Early work on integral attachment design focused on the analysis of particular types of locking features such as cantilever hooks [8], bayonet-fingers [9], compressible hooks [10]. More recently, Genc *et al*.[11-13] discussed a feature-based method to integral attachment design, which classified snap-fit features into three categories: locating features, locking features, and enhancing features. Luscher *et al*. [14] discussed a similar classification based on assembly motions. These works, however, did not address the reversible snap-fit designs that are actuated by indirect means such as localized heating.

Design of Reversible Joints

Chiodo *et al*. [15] developed the concept of active disassembly using smart materials (ADSM), where heat-induced disassembly is realized by self-disengaging fasteners made of shape memory polymers (SMP) and compression springs. Li *et al*. reported topology optimization of heat-reversible cantilever snaps [16,17,18], where unsnapping is realized by the local transient thermal deformations of the cantilevers. Although effective in the presented examples, these works have not found many applications due to the need of special, costly, and unstable materials [15] or snaps with impractically small locking surfaces and low stiffness [16,17,18]

Our previous work [19,20] introduced an initial concept of high-stiffness, heat-reversible locator-snap systems that realizes non-destructive disassembly of plastic automotive body panels from aluminum frames. Similar to the design concept presented in this paper, it converts the in-plane thermal expansion of a body panel constrained on a rigid frame by locators, to out-of-plane bulging large enough to unlock the snap that locks the panel and the frame. However, the concept is specifically developed for assemblies of a semi-planar elastic panel and a rigid frame. Also, the design method discussed in [19,20] assumes the orientations of locators and snaps given as inputs, and only optimizes the numbers and locations of locators and snaps in the given orientations and the area of heating. Since the orientations of locators and snaps largely determine the design's ability to balance elasticity for snap release and stiffness for joint sustaining, the method was incapable of full exploration of design space.

The method discussed in this paper generalizes the concept in [19,20] to be applicable to any thin-walled enclosure assemblies with arbitrary mating lines, and extends the design method in [19,20] to include the orientations of locators and snaps as additional design variables.

Screw Theory in Motion and Constraint Analysis

The Screw Theory, a pioneering work by Ball [21], is used for motion and constraint analysis of rigid bodies. Waldron [22] utilized the Screw Theory to build a general method to determine all relative degrees of freedom (DOF) between two rigid bodies making contacts to each other. Extending the work by Konkar and Cutkosky [23], Adams and Whitney [24,25] developed a method to determine the status (over-, under- or fully constrained) of rigid body assemblies with mating features. Their method also determines the motion type and range of under-constrained rigid body assemblies. Lee and Saitou [26] applied their method for automatically synthesizing 3D assemblies with prescribed in-process dimensional adjustability. Our previous work [20] outlined the use of the Screw Theory to analyze relative motion constraints on a panel and a frame imposed by locators and snaps of given orientations. This approach is applied in this paper for pre-calculating a set of all feasible orientations of locators and snaps to be examined during optimization.

METHOD

Overview

The method synthesizes optimal designs of the locator-snap system by solving the following optimization problem:

- **Given:** the geometry of the two mating thin-walled parts, the coordinates of the vertices of the polygon representing the mating line where locators and snaps will be placed, the feasible region for heating, and the library of locators and snaps that can be used.
- **Find:** orientations, numbers, and locations of locators and snaps, and number, locations and sizes of heating areas.
- **Minimizing:** the total heated area to unlock the snaps, and the deformation at the mating line under own weight.
- **Subject to:** the parts are under constrained and do not interfere with the neighboring parts before snap engagement, the parts are not under constrained and meet any structural requirements after snap engagement, local heating induces displacement sufficient for unlocking snaps, and uniform heating does not induce displacement sufficient for unlocking snaps.

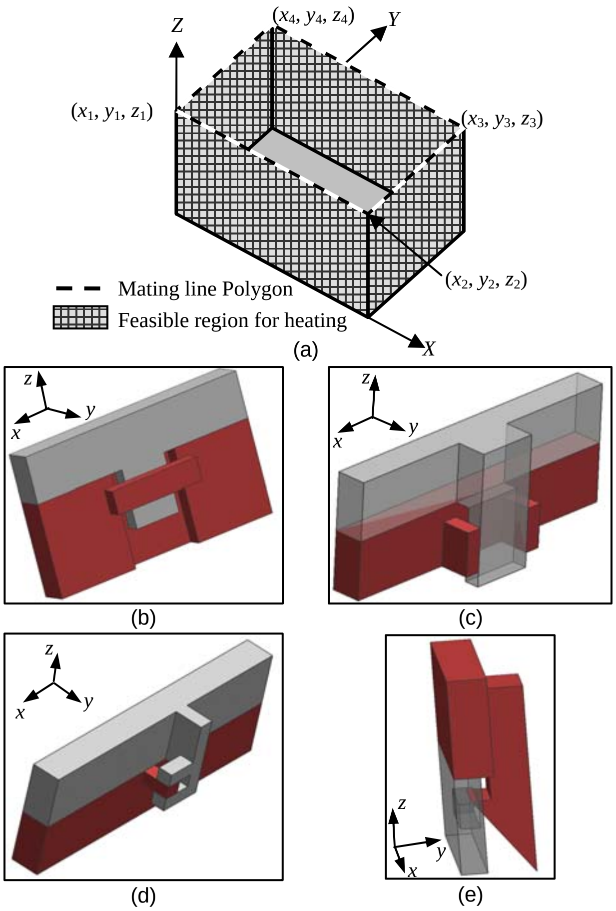


Figure 2. (a) part geometry (only one part shown), coordinates of vertices of mating polygon, and feasible region for heating. (b)-(e) locators and snaps in library.

Figure 2 shows example inputs. In addition to the actual geometry of feasible locators (and the associated protrusions) and snaps (and the associated catches) available for a given problem (Figures 2b-e), the library contains the wrench matrix representing the motion constraints imposed by each locator and snap, with respect to its local coordinate system. For example, the locator in Figure 2b constrains the motion in ±*y* and +*z* directions in local coordinates. The locator in Figure 2c constrains the motion in ±*x* and +*z* directions in local coordinates. The locator in Figure 2d constrains the motion in ±*z* directions in local coordinates. Finally, the snap in Figure 2e constrains the motion in +*z* direction in local coordinates. The optimization problem is solved using a multi-objective genetic algorithm (MOGA) [27,28] coupled with structural and thermal Finite Element Analysis.

Generation of feasible orientations of locators and snaps

In order to avoid examining a large number of infeasible designs during optimization, a set of all orientations of locators and snaps feasible to the motion constraints of the above optimization problem is pre-calculated using the Screw Theory. It is assumed that:

- Locators (and the associated protrusions) and snaps (and the associated catches) can be placed on either of the two mating parts.
- Locators (and the associated protrusions) and snaps (and the associated catches) can be placed only at predefined discrete locations (*eg.*, nodes of finite elements) on the internal surfaces along the edges of the mating polygon and only in predefined discrete orientations (*eg.*, a subset of 0^o, 90^o, 180^o, or 270^o) relative to the edge.
- Each edge of the mating polygon can have one or more locators (or the associated protrusions) or snaps (or the associated catches) only of the same type, only in the same orientation.
- Each edge of the mating polygon can have either locators (or the associated protrusion) or snaps (or the associated catch), but not both.

Based on the above assumptions, all possible combinations of locators, snaps, orientations, and edges can be enumerated. Since each edge can only have locators or snaps of the same type in the same orientation, their numbers and locations along each edge can be ignored for the purpose of the analysis of motion constraints. Since relative motion constraints on an edge are independent of the choice of the part (*eg.*, top cover or bottom cover) on which the locators or snaps are placed, this choice can also be ignored for the purpose of the analysis of motion constraints. As such, a combination of locators, snaps, orientations, and edges can be represented as

$$\mathbf{z} = (c_1, c_2, \ldots, c_n) \tag{1}$$

$$c_i = (l_i, o_i); \quad i = 1, 2, \ldots, n \tag{2}$$

where n is the number of edges in the mating polygon, l_i and o_i are a locator or a snap in the library (*nil* if no locator/snap) and an orientations among the predefined choices (ignored if l_i=*nil*), respectively, of the i-th edge. Each combination z of locators, snaps, orientations, and edges is tested against two motion constraints in the above optimization problem: 1) the parts are under constrained and do not interfere with neighboring parts before snap engagement and 2) the parts are not under constrained (*i.e.,* can be over constrained) after snap engagement. After testing, only the combinations that satisfy both conditions are stored in a set F of feasible orientations to be examined during optimization.

Examples in Figure 3 illustrate the two motion constraints. It the figure, it is assumed a locator can constrain the normal direction (positive and negative) of the surface on which it is placed and its direction of insertion (–z in the Figure), a snap can only constrain its direction of disengagement (+z in the Figure), and there is no neighboring part that might cause interferences. In the orientations shown in Figure 3a, the both conditions are satisfied. Locators l_1 and l_2 constrain the motions in the $\pm x$ and $-z$, and $\pm y$ and $-z$ directions respectively, but nothing constrains the $+z$ direction. After snapping, snap S_1 and S_2 provides the constraint in this direction, thereby fully constraining the two mating parts. In the orientations shown in Figure 3b, on the other hand, the second condition is not satisfied. Locators l_3 and l_4 constrain the motion only in the $\pm x$ and $-z$ directions, whereas snaps s_3 and s_4 constrain the $+z$ direction. As a result, this is under constrained as it is free to move in the $\pm y$ direction.

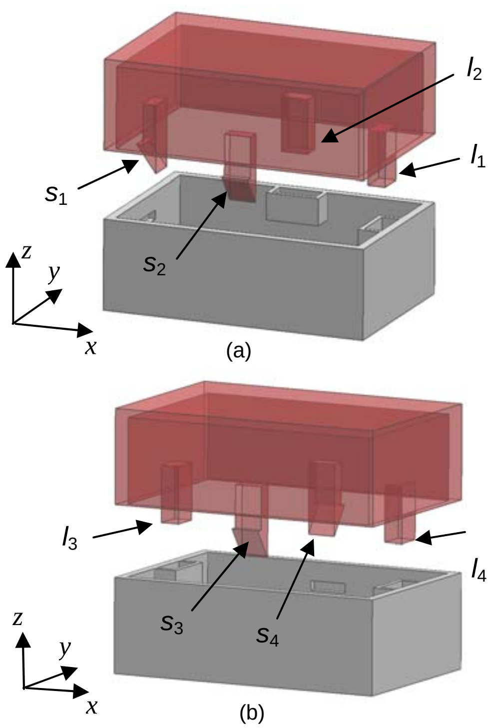


Figure 3. Examples of two different locator and snap orientations

The above conditions can be more precisely expressed using the Screw Theory [21]. Adopting the wrench matrix representation similar to [20,26], for example, the locators and snaps in Figure 3 are represented as:

$$\mathbf{W}_{l_1} = \mathbf{W}_{l_3} = \mathbf{W}_{l_4} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix} \tag{3}$$

$$\mathbf{W}_{l_2} = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix} \tag{4}$$

$$\mathbf{W}_{s_1} = \mathbf{W}_{s_2} = \mathbf{W}_{s_3} = \mathbf{W}_{s_4} = \begin{pmatrix} 0 & 0 & -1 & 0 & 0 & 0 \end{pmatrix} \tag{5}$$

where each row represents the directional (row) vectors of the force and moment in the global reference frame, which can be supported by a mating surface in a locator or a snap. For example, the 1st row in Equation 3 has –1 at the 1st column, indicating the upright surface of locator l_1 can support the force in $+x$ direction. Note that the moments (the 4th, 5th, and 6th columns) are ignored due to our primal concern on the translational degrees of freedom. This is justified by using wide locators and snaps. In testing each combination of locators, snaps, orientations, and edges in the enumerated set, the wrench matrix of a locator or a snap placed on an edge in an orientation is transformed to the one with respect to the global reference frame, using the rotation matrix constructed from the directional cosines of the edge and the rotation matrix for the orientation.

Based on the principle of virtual work, the forces and moments represented by wrench matrix $\mathbf{W} = (\boldsymbol{w}_1,\ldots,\boldsymbol{w}_n)^{\mathrm{T}}$ constrains the motions represented by twist matrix $\mathbf{T} = (\boldsymbol{t}_1,\ldots,\boldsymbol{t}_m)^{\mathrm{T}}$ if and only if there exists a negative component in every column of the virtual coefficient matrix [24]:

$$\Delta(\mathbf{W},\mathbf{T}) = \begin{pmatrix} \delta(\boldsymbol{w}_1,\boldsymbol{t}_1) & \cdots & \delta(\boldsymbol{w}_1,\boldsymbol{t}_m) \\ \vdots & \ddots & \vdots \\ \delta(\boldsymbol{w}_n,\boldsymbol{t}_1) & \cdots & \delta(\boldsymbol{w}_n,\boldsymbol{t}_m) \end{pmatrix} \tag{6}$$

where $\sigma(\boldsymbol{w},\boldsymbol{t})$ is the virtual coefficient of wrench $\boldsymbol{w} = (\boldsymbol{f}^T, \boldsymbol{m}^T)$ and twist $\boldsymbol{t} = (\boldsymbol{\omega}^T, \boldsymbol{v}^T)$:

$$\delta(\boldsymbol{w},\boldsymbol{t}) = \boldsymbol{v}\bullet\boldsymbol{f} + \boldsymbol{\omega}\bullet\boldsymbol{m} \tag{7}$$

Equivalently, this can be written as:

$$\text{fully-constrained}(\Delta(\mathbf{W},\mathbf{T})) = \begin{cases} \textit{true} & \text{if } \forall j, \exists i,\ \delta(\boldsymbol{w}_i,\boldsymbol{t}_j) < 0 \\ \textit{false} & \textit{otherwise} \end{cases} \tag{8}$$

Equation 8 gives a compact representation of the above two conditions for feasible locators and snap orientations:

$$\text{fully-constrained}(\Delta(\bigcup_{k\in L}\mathbf{W}_k,\mathbf{T}_{all})) = \textit{false} \quad (9)$$

$$\text{fully-constrained}(\Delta(\bigcup_{k\in L\cup S}\mathbf{W}_k,\mathbf{T}_{all})) = \textit{true} \quad (10)$$

where L and S are the sets of locators and snaps, respectively, and $\mathbf{W}_k$ is the wrench matrix of a locator (if $k \in L$) or a snap (if $k \in S$), and $\mathbf{T}_{all}$ is the twist matrix of all translational motions in $\pm x$, $\pm y$, and $\pm z$ directions:

$$\mathbf{T}_{all} = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{pmatrix} \quad (11)$$

Using Equations 3 and 4, for example, the virtual coefficients matrix for Figure 3a before snap engagement is given as:

$$\Delta(\bigcup_{k\in\{l_1,l_2\}}\mathbf{W}_k,\mathbf{T}_{all}) = \begin{pmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 1 & -1 & 0 & 0 \\ 0 & 0 & -1 & 1 & 0 & 0 \end{pmatrix} \quad (12)$$

Since the 5th column has no negative entry, fully-constrained = *false*. If $\mathbf{W}_{s1}$ and/or $\mathbf{W}_{s2}$ are added, *i.e.* snaps are engaged, the virtual coefficients matrix will have at least one negative entry in each row, thus fully-constrained = *true*. On the other hand, the virtual coefficients matrix for the design in Figure 3b after snap engagement is given as:

$$\Delta(\bigcup_{k\in\{L_1,L_2\}\cup\{S_1,S_2\}}\mathbf{W}_k,\mathbf{T}_{all}) = \begin{pmatrix} 1 & -1 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 0 & -1 & 1 \end{pmatrix} \quad (13)$$

Since the matrix does not have negative values in $+y$ or $-y$ axis, Equation 10 is not satisfied; the design is always under-constrained in the y direction.

Since Equations 9 and 10 do not prohibit over constraining of the panel, the same degree of freedom can be constrained by multiple locators and/or snaps. While this may cause undesirable tolerance stack-up, the dimensional tolerances of the panel and frame are assumed to be sufficiently small in the following case study. The issue of over constrained and tolerance stack-up, however, will be addressed as a part of future work.

Simultaneous optimization of locators/snaps and heating areas

In addition to the satisfaction of motion constraints, an enclosure assembly must satisfy the following thermal and structural requirements:

1. Snaps do not unlock due to the own weight of the assembly.
2. Local heating induces displacement sufficient for unlocking snaps
3. Uniform heating does not induce displacement sufficient for unlocking snaps.
4. Any thermal and structural requirements other than requirement 1, for the desired functions of the product.

Requirement 1 is for preventing accidental disassembly during the regular use of the product. In the optimization problem stated earlier, it is regarded as one of two objective functions to be minimized, together with the total heating area to unlock the snaps. Requirement 2 is for the desired reversal behavior of locator-snap system. Requirement 3 is for preventing accidental disassembly during the use in an elevated temperature. Examples of requirement 4 include guard against thermal damage and resonance vibration. Although not explicitly imposed, use of multiple heating locations can also facilitate the prevention of accidental disassembly in a lock-n-key fashion, which can be observed in some results in the following case study.

The following four design variables are defined for the simultaneous optimization of locators/snaps and heating areas:

- $\boldsymbol{x} = (x_1, x_2, \ldots, x_n)$ where x_i is a vector of the id's of d finite element nodes on edge i on which locators or snaps are placed; $x_{ij} = nil$ if the j^{th} locator/snap is not placed on edge i.
- $\boldsymbol{y} = (y_1, y_2, \ldots, y_m)$ where y_i is the coordinate vectors of the four vertices of the i-th rectangular area to be heated; $y_i = nil$ if the i-th heating area is undefined.
- $\boldsymbol{z} = (c_1, c_2, \ldots, c_n)$ where $c_i = (l_i, o_i)$ are a choice of locator/snap and its orientation of the i-th edge as defined in Equation 2; $l_i = nil$ if the i-th edge does not have a locator/snap, in which case the value of o_i is ignored.

Using $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$, the optimization problem can be written as:

$$\text{minimize } \{ f_1(\boldsymbol{y}),\ f_2(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z})\}$$

subject to:

$$\text{min\_displacement}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}) > h_+$$
$$\text{max\_displacement}(\boldsymbol{x},\boldsymbol{z}) < h_-$$
$$\text{structural\_requirements}(\boldsymbol{x},\boldsymbol{z}) = \textit{true}$$
$$x_{ij} \in \{nil, L_i, L_i+1, \ldots, U_i\};\ i = 1, \ldots, n;\ j = 1, \ldots, d$$
$$y_i \in P_h^{\,4};\ i = 1, 2, \ldots, m$$
$$\boldsymbol{z} \in F$$

where:

- $f_1(\boldsymbol{y})$ is the area enclosed by the squares defined in $\boldsymbol{y}$.
- $f_2(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ is the maximum deformation at the mating line under own weight of the product during snap engagement.
- min_displacement($\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$) is the minimum outward steady state thermal displacement of all nodes on which snap-catch pairs are placed, when locally heated at temperature T_l in the locations specified by $\boldsymbol{y}$.
- max_displacement($\boldsymbol{x}$, $\boldsymbol{z}$) is the maximum outward steady state thermal displacement of all nodes on which snap-catch pairs are placed, when uniformly heated at temperature T_u ($< T_l$).
- h_+ is the height of snaps plus a small tolerance
- h_- is the height of snaps minus a small tolerance
- structural_requirements($\boldsymbol{x}$, $\boldsymbol{z}$) is any structural requirements (other than f_2) during snap engagement.
- L_i and U_i are lower and upper bounds of the node numbers of the finite elements on edge i, respectively.
- P_h is the feasible region of the heating area.
- F is the set of feasible combination of locators, snaps, orientations, and edges generated as discussed in the previous section.

The evaluation of min_displacement($\boldsymbol{x}$, $\boldsymbol{y}$, $\boldsymbol{z}$) and max_displacement($\boldsymbol{x}$, $\boldsymbol{z}$) requires thermal-structural FEA, whereas $f_2(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$ and structural_requirements($\boldsymbol{x}$, $\boldsymbol{z}$) requires structural FEA only.

It should be noted variables $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{z}$ do not explicitly specify the choice of the part (*eg.*, top cover or bottom cover) on which a locator or a protrusion, or similarly a snap or a catch, should be placed. Since the choice does not affect the motion constraints and structural behavior during snap engagement, it can be arbitrary in the case of a locator-protrusion pair. In the case of a snap-catch pair, the choice is determined based on the thermal deformation upon heating. If the surface of a part bulges outwards, a catch is placed on the part. If the surface bulges inwards, a snap is placed on the part.

CASE STUDY

Inputs

The method is applied to a DVD player made of two mating pieces of injection molded Nylon 66-30% glass filled enclosure. The DVD player geometry is 250×500×150mm with a T-shaped mating line and wall thickness of 1.5 mm. The material properties are given in Table 1. Figure 4 shows the simplified model of a case assembly of the DVD player.

Figure 5 shows the FE model of the lower part of the assembly. The mating polygon has 8 edges (n = 8), shown as thick black lines and labeled as $e_1 \ldots e_8$. The feasible heating region, P_h, is considered as all the 8 surfaces of the lower part except its base surface. To facilitate the simplified mapping of the coordinates in $\boldsymbol{y}$ to the heading areas as discussed below, the feasible heating region is subdivided into ten (10) sub-surfaces (labeled as $S_{1L} \ldots S_{5L}$ and $S_{1R} \ldots S_{5R}$), five (5) on each side of the plane of symmetry, as shown in Figure 5.

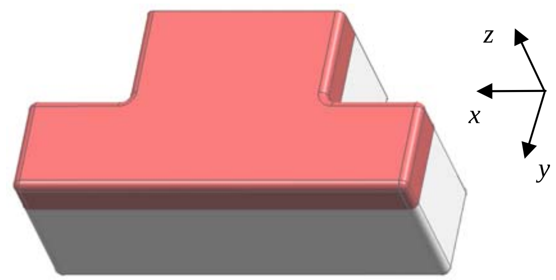


Figure 4. Simplified model of case assembly of a DVD player.

Table 1. Material properties of Nylon 66-30% glass filled.

Property Name (units)	*Value*
Density (g/cm3)	1.36
Elasticity modulus (MPa)	8500
Poisson Ratio	0.36
Melting point (^{o}C)	260
Thermal expansion coefficient (μm/m.^{o}C)	30.0
Specific heat capacity (j/kg.^{o}C)	1800
Conductivity (W/m.^{o}K)	0.40

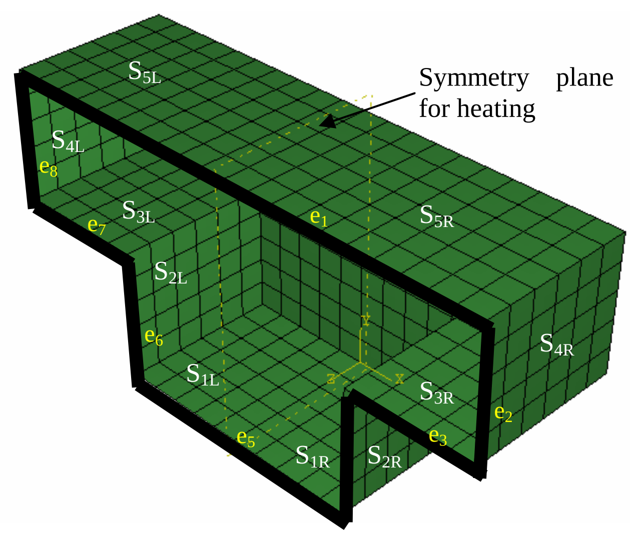


Figure 5. FE model of the lower part of assembly showing edges and feasible heating region.

Generation of the feasible locator and snap orientations

A set of feasible orientations of locator and snaps are pre-calculated as discussed earlier. The locator and snap library used in this case study consists of those shown in Figure 2b and Figure 2d and they have the same wrench matrices as in Equations 3-5. Only the orientations shown in Figure 3 are considered. After testing 256 possible combinations for

Equations 9 and 10, only 224 are feasible and are included in the feasible set F. In all cases, the assembly direction is to move the two parts toward each other in the z direction in Figure 4.

Simultaneous optimization of locators and heating areas

In order to simplify the specification of heating area by $\boldsymbol{y}$, the feasible heating regions of two symmetric halves of the enclosure are first flattened to rectangular regions as shown in Figure 6a, and the coordinates in $\boldsymbol{y}$ are then applied on this transformed geometry. Instead of utilizing variable $\boldsymbol{y}$ to explicitly define m heading areas, the case study considers up to two (2) rectangular heating areas by using $\boldsymbol{y}$ with m = 1 and an auxiliary design variable t defined as:

$$t = \begin{cases} 0 & \text{if only left (L) side is heated} \\ 1 & \text{if only right (R) side is heated} \\ 2 & \text{if both sides are heated} \end{cases} \quad (14)$$

where the left (L) and right (R) sides are with respect to the surface of symmetry as defined in Figure 5. A sample heated area is shown in Figure 6a and its equivalent area in the 3D model is shown in Figure 6b. If t = 0 instead of 1 in Figure 6b, the heated area would have been on the other side (grey region).

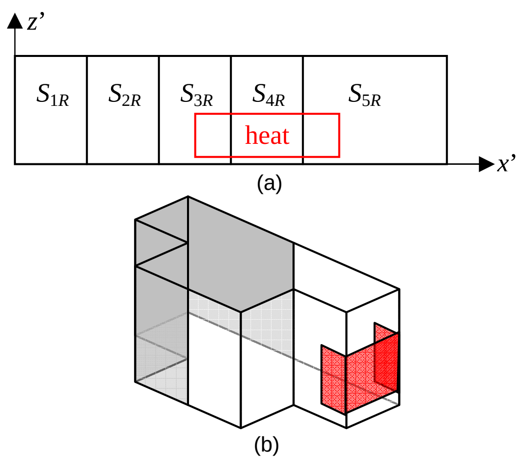


Figure 6. (a) heating area in flattened feasible heating sub-region S_{1R}-S_{5R}, and (b) corresponding heating area in 3D.

The heating temperatures for local heating and uniform heating are T_l = 200°C and T_u = 50°C, respectively, in a room of 20°C. During heating, free convection to the air (convection heat transfer coefficient = 8 W/m^2.°K) is considered as the only source of heat dissipation. It is assumed each edge can have only one locator or snap (d = 1).

For calculation of $f_1(\boldsymbol{y})$, the number of heated nodes is taken as a measure of the heated area. For calculation of $f_2(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$, a uniformly distributed load of 20 N is applied to the base surface of an enclosure part in ±x, ±y, and -z directions, and the maximum displacement of the nodes on the mating line for all loadings is obtained.

A penalty is applied if the minimum displacement of all nodes with snaps under local heating at T_l = 200°C is less than h_+ = 1 mm. Since MOGA does not handle constraints explicitly, the minimum displacement constraint is written as a penalty function as:

$$f_3(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = \max(0, h_+ - \text{min\_displacement}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})) \quad (15)$$

Similarly, a penalty is applied if the maximum displacement of all nodes with snaps under uniform heating T_u = 50°C is less than h_- = 0.5 mm:

$$f_4(\boldsymbol{x}, \boldsymbol{z}) = \max(0, \text{max\_displacement}(\boldsymbol{x}, \boldsymbol{z}) - h_-) \quad (16)$$

Table 2 shows the GA parameters. Heuristic and arithmetic crossovers are used for all the variables.

Table 2. GA parameters used in the case study

Parameter	*Value*
Population size	80
Number of generations	160
Crossover probability	0.95
Mutation probability	0.05

Optimization Results

Figure 7 Shows the Pareto Optimal solutions, which exhibit a trade-off between the part compliance and the amount of heating required (number of heated nodes). The solutions above the dotted line use single heating area on one side of the DVD (t = 0 or 1), while the solutions below the line use symmetric heating (t = 2).

Figure 8 shows the optimal placement of locators and snaps and the response due to local heating of the solution with minimum heating area (solution 1). The heating area is 25 mm x 575 mm (48 nodes). Locator positions are marked with black circle, while snap positions are marked with an arrow showing the bulging direction. If the bulging is outward, a catch and a snap are placed on the shown part and the other part (not shown), respectively. The maximum deformation at the mating line under its own weight is due to pressure load in +y direction at the upper surface and is (0.7292 mm).

Figure 9 shows the optimal placement of locators and snaps and the response due to local heating of an optimum solution with minimum symmetric heating areas (solution 7). The heating area is 150 mm x 150 mm x 2 (98 nodes). The maximum deformation at the mating line under its own weight is due to pressure load in –z direction at the bottom surface and is (0.3038 mm). If only one side (either left side or right side) is heated, only one snap will unlock while the other snap will remain closed as shown in Figures 10a and 10b. As a result, both sides need to be heated simultaneously to allow unlocking.

Figures 11 (a) and (b) and Figures 12 (a) and (b) show CAD drawings of top cover and base part of the final optimized DVD player model for optimum solutions 1 and 7, respectively. Appendix A shows the remaining Pareto optimum results.

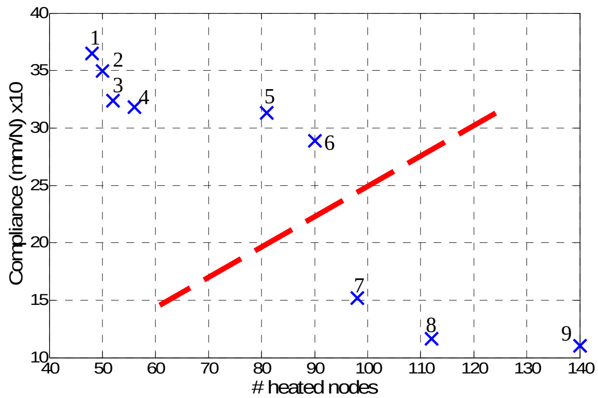


Figure 7. Pareto optimal solutions for the case study.

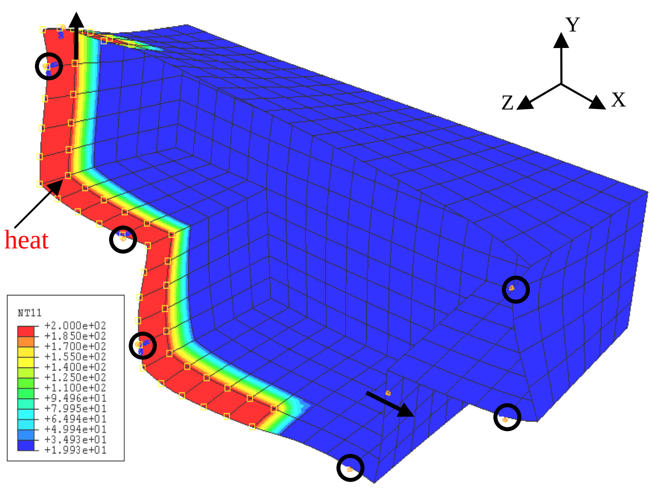


Figure 8. Optimum solution with minimum heat area (solution 1)

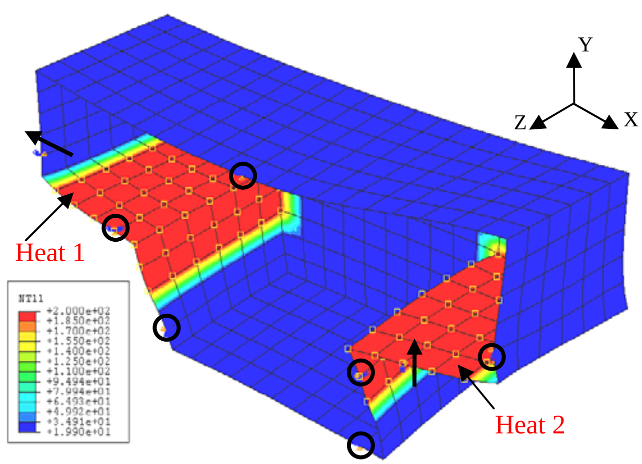
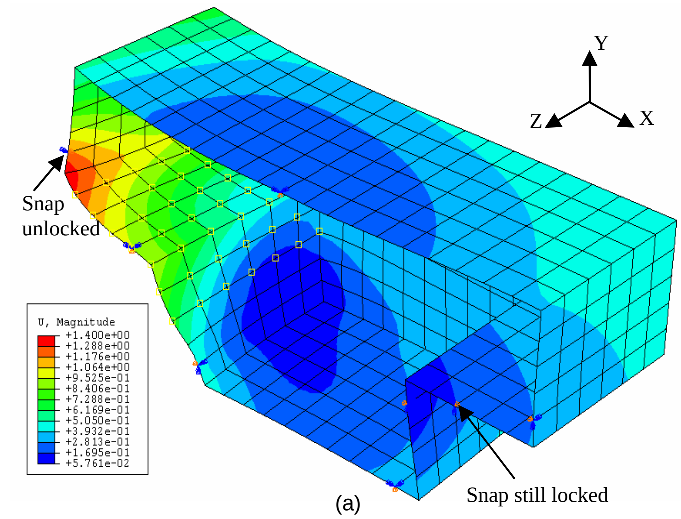


Figure 9. Optimum solution with minimum symmetric heat area (solution 7)



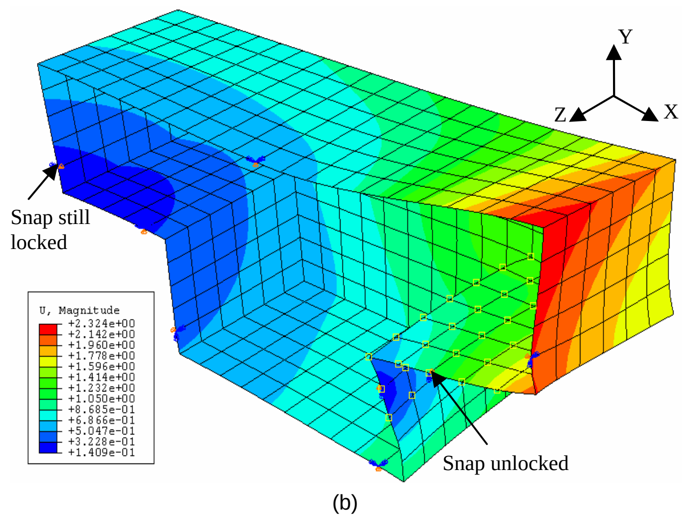
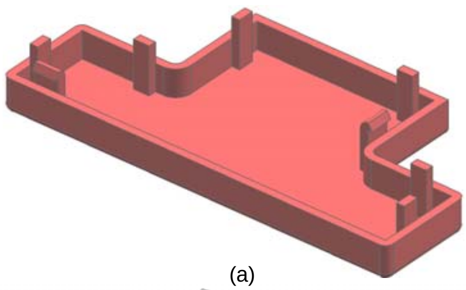


Figure 10. solution 7 response to one sided heating, (a) area 1 is heated, and (b) area 2 is heated.

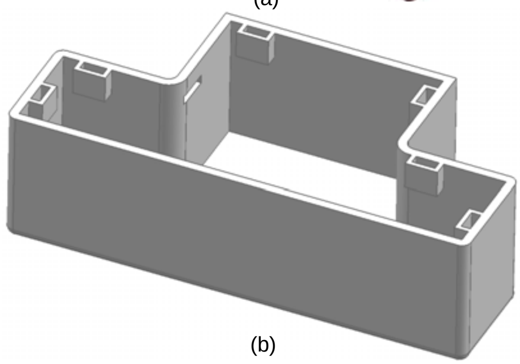
CONCLUSION AND FUTURE WORK

This paper presented a unified method for designing a high-stiffness reversible locator-snap system that can be disengaged non-destructively with localized heat. The method was applied to a case study on a DVD player enclosure with a T-shaped mating line. The resulting Pareto-optimal solutions exhibit alternative design with different trade-offs between structural stiffness during snap engagement and heating area necessary for snap disengagement. Some results require simultaneous heating of two areas, demonstrating the idea of a lock-n-key.

Future work includes the explicit inclusion of lock-n-key separation into the problem formulation, addressing the issue of undesired tolerance stack-up due to the use of multiple locators, and extending the problem formulation to generic 3D geometries relaxing some or all assumptions made in the present study.

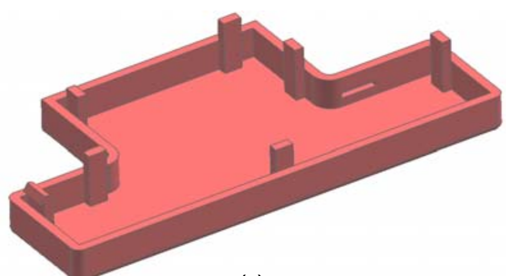


(a)

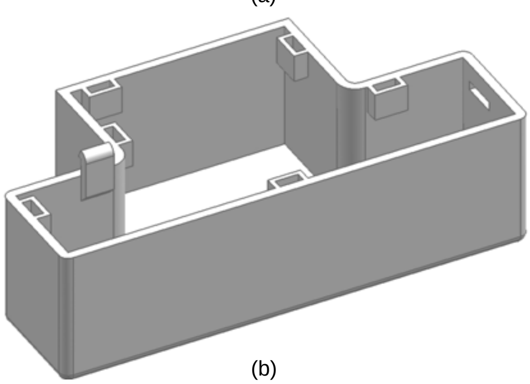


(b)

Figure 11. CAD drawing for the optimized DVD player model (solution 1) (a) top part, (b) base part.



(a)



(b)

Figure 12. CAD drawing for the optimized DVD player model (solution 7) (a) top part, (b) base part.

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APPENDIX A

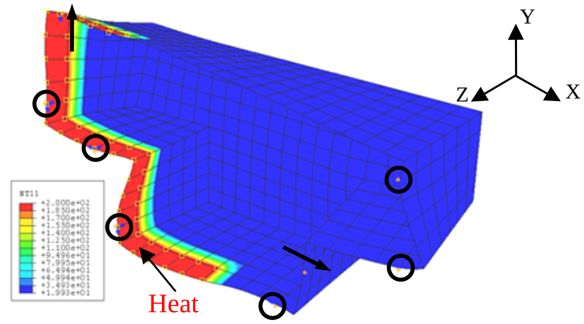

Figure A1. Optimum solution #2

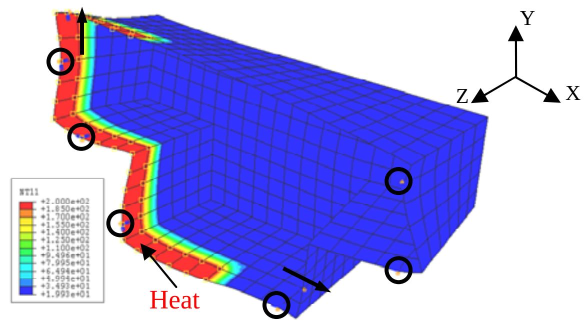

Figure A2. Optimum solution #3

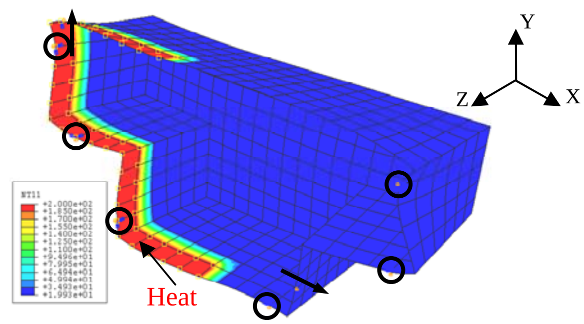

Figure A3. Optimum solution #4

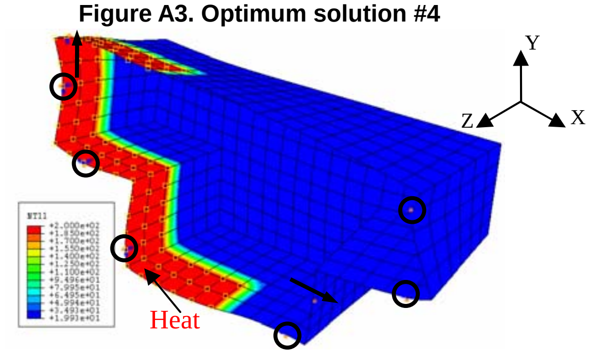

Figure A4. Optimum solution #5

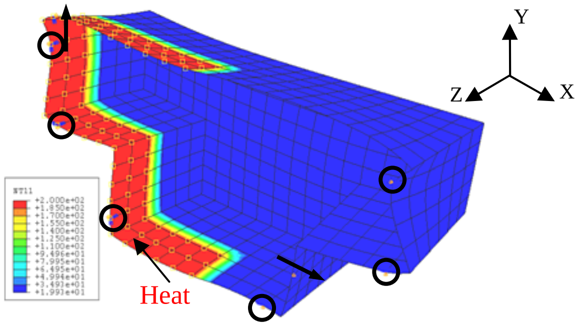

Figure A5. Optimum solution #6

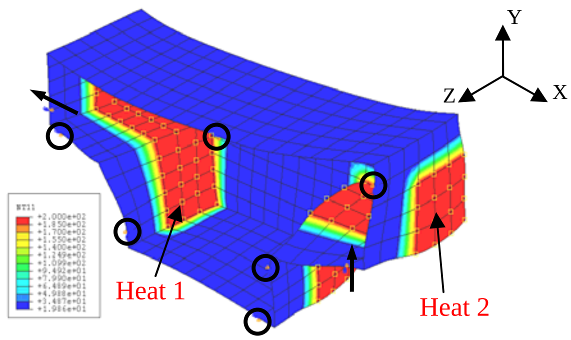

Figure A6. Optimum solution #8

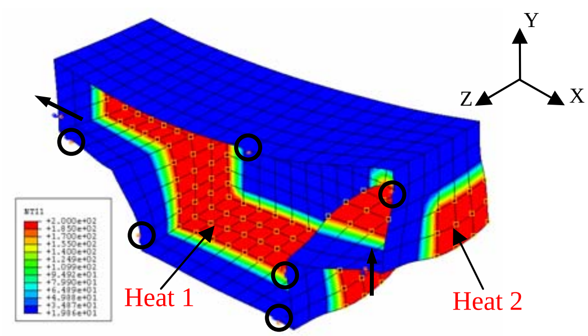

Figure A7. Optimum solution #9