OPTIMIZATION OF MULTIPLE PANEL FITTING IN AUTOMOBILE ASSEMBLY

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ABSTRACT

A systematic approach is presented to obtain improved panel fit quality through the use of an optimum panel fitting strategy. The objective of the optimal panel fitting strategy is to determine the location of the panels on the automobile body such that the gap and flush variation of the panel fit are minimized. This approach uses measurement data from both the panels and the body-in-white (BIW) to determine the optimum position of multiple panels in an automobile body opening. First, some indices are defined to quantify the quality of a panel fit. Second, the sources of variation in the gap and flush are presented. Then the multiple panel fitting problem is formulated into a constrained optimization model. The effects of the optimization process for multiple panels are then demonstrated and validated through the use of computer simulation. The computer simulation demonstrates the optimization model and algorithm by reducing the within-car gap and flush variation on average by 24.3% and by as much as 43.4% in the case study presented.

INTRODUCTION

In today's highly competitive automobile market the quality of the product is becoming increasingly important. Among the quality concerns of the automobile manufacturers is the quality of the fit and finish. Specifically, the quality of the panel fits of the automobile ranks high in concern due to the high warranty costs. An inadequate panel fit will contribute not only to functional problems such as water leakage and wind noise but aesthetic problems such as uneven gap and flush.

The indices that are used to determine the quality of the panel fit are the gap and flush variation, gap range and flush range. These terms will all be defined more rigorously later in the paper. The dimensional variations of the gap and flush between the BIW and the panel, or between panels, arise from four sources which are (figure 1): (1) dimensional variation of the panels; (2) dimensional variation of the BIW; (3) variation of the panel fitting process; and (4) effects of painting and general assembly. Each branch of the fishbone diagram shown bellow has various sources of variation which effect the gap and flush variation.

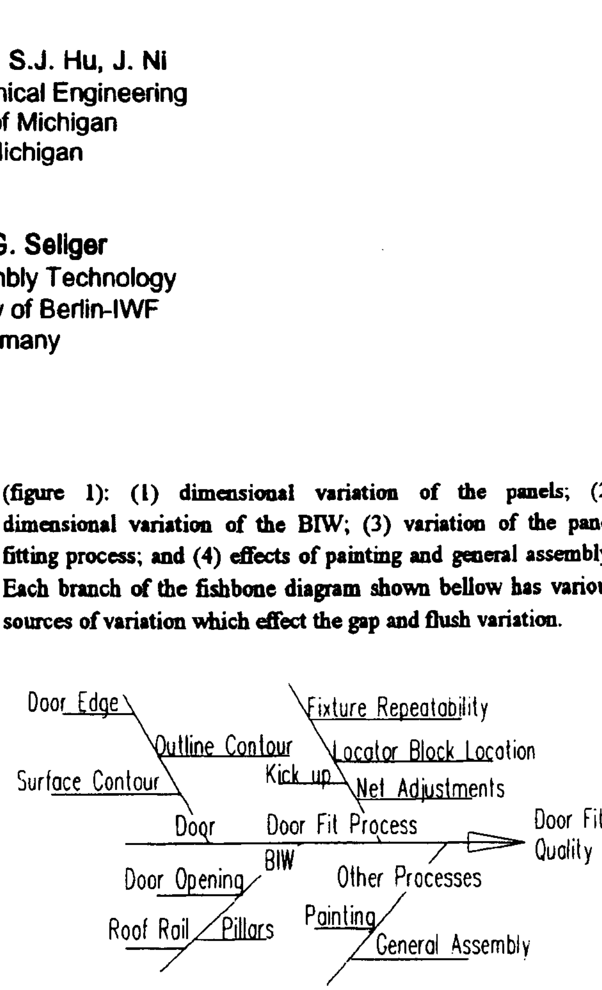

FIGURE 1: FISH BONE CHART OF VARIATION COMPONENTS IN PANEL FITTING

The first two variations are subassembly variations and need to be improved at the subassembly level. These issues have been addressed by Wu and Hu (1990). The fourth source of variation is a topic of research outside the range of this paper. This paper focuses on the variation induced by the panel fitting process. In this paper, a special example of panel fitting, automobile doors, is used to demonstrate the optimization process

The control of dimensional deviation in the automobile industry has been mainly done by feeding Statistical Process Control (SPC) data back to manufacturing processes such as stamping or part subassembly, Wu and Hu (1990). Fitting of rigid bodies in general was suggested by Bonna and Menga (1984) which presents a general constrained optimization process of a single body. An approach to integrate the data directly to the fitting process was proposed by Wu, Hu, and Wu (1994) where the best fitting parameters are transformed to a door fixture location. However, Wu et al. (1994) described the best fitting process in which only one door was fit at a time. Recently, Schuler, Zussman, and Seliger (1994) and Sakai and Yasumatsu (1993) presented an approach that is based on 100% measurements to determine the position of a single panel based on different location criterion. However, little literature exists in the area of multiple body fitting optimization.

In recent years, the implementation of the in-line Optical Coordinate Measurement Machine (OCMM) in the automotive industry and the increasing accuracy of industrial robots provide new opportunities for the development of a flexible assembly system for the fitting of automobile panels. This flexible assembly system attempts to find the optimum position of the doors in the BIW such that the within-car gap and flush variation is minimized. In this approach, multiple doors are to be fit simultaneously so that the dimensional deviation in the various parts can be distributed evenly over the entire door fit of the automobile by the optimization process. However, effective implementation of this multiple panel fit optimization remains a challenge. Some of these challenges can be summarized as follows:

1. *Transformation of the discrete OCMM measurement data to a geometric model of the panel fit.*
2. *Formulation of an optimization objective function to minimize the within-car gap and flush variation.*
3. *Formulation of constraints to restrict the optimization problem.*

In this paper, a systematic approach to obtain optimum multiple panel fitting is presented based on a constrained optimization problem. The approach is demonstrated by locating the front and rear doors of an automobile simultaneously. Constraints that are taken into account are Euler parameter constraints, minimum gap constraints and minimum parallelism constraints. The organization of the paper is as follows: Section 2 describes the geometric model of multiple panel fitting. Section 3 presents the constrained multiple panel optimization scheme. Section 4 verifies the proposed method through computer simulations. In section 5, sensitivity analysis was performed on the optimization constraints. The conclusions of the paper are discussed in the section.

GEOMETRIC MODEL

The objective of the optimization model is to minimize the variation in the gap and flush. Essentially, the gap and flush are projections of the vector, $\overline{V}$, from the Door to the BIW at the measurement points. The projection of this vector, $\overline{V}$, onto the vectors GP_i and FP_i at the specific point will result in the measure of the gap and flush respectively. The vectors GP_i and FP_i are unit vectors which define the direction of the gap and flush at a specified point i (figure 2). The direction of these vectors is governed by the design of the gap and flush. Essentially, the gap vector, GP_i, is the unit vector tangent to the design direction of the vector $\overline{V}$, Similarly, the flush vector, FP_i, is the unit vector perpendicular to the design direction of the vector $\overline{V}$,. An illustration of the gap and flush measures is shown in figure 2.

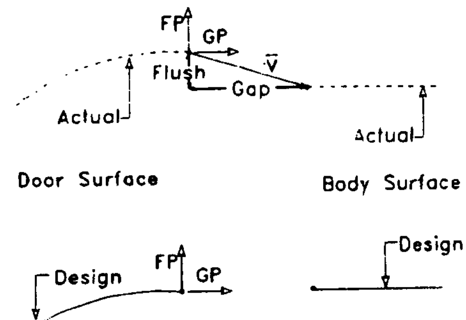

FIGURE 2: ILLUSTRATION OF GAP AND FLUSH

As mentioned, a panel is defined as any sheet metal part attached to the BIW. The doors, hood, fender, and hatch are examples of panels. Definitions of other terms used throughout this paper are:

$\mathbf{B}_j$ = the coordinates of the jth point on the body
$\mathbf{D1}_j$ = the coordinates of the jth point on the front door
$\mathbf{D2}_j$ = the coordinates of the jth point on the rear door
$\mathbf{T1}(\mathbf{X}_i)$ = Front door homogeneous transformation matrix (4x4).
$\mathbf{T2}(\mathbf{X}_i)$ = Rear door homogeneous transformation matrix (4x4)

$$T\bullet(X_i)=\begin{bmatrix} Q_{3\times3} & P_{3\times1} \\ 0_{1\times3} & 1 \end{bmatrix}$$

Q_{3X3} = Coordinate Rotational Matrix

$$Q_{3X3} = 2*\begin{bmatrix} e_0^2+e_1^2-\frac{1}{2} & e_1e_2-e_0e_3 & e_1e_3+e_0e_2 \\ e_1e_2+e_0e_3 & e_0^2+e_2^2-\frac{1}{2} & e_2e_3-e_0e_1 \\ e_1e_3-e_0e_2 & e_2e_3+e_0e_1 & e_0^2+e_3^2-\frac{1}{2} \end{bmatrix}$$

where, e_i's are euler parameters

P3x1= Coordinate translation matrix = $\begin{bmatrix} R_x & R_y & R_z \end{bmatrix}^T$

Where R_x, R_y, and R_z are translation values in the x, y, and z coordinates. Thus,

$$T\bullet(X_i)=2*\begin{bmatrix} e_0^2+e_1^2-\frac{1}{2} & e_1e_2-e_0e_3 & e_1e_3+e_0e_2 & R_x/2 \\ e_1e_2+e_0e_3 & e_0^2+e_2^2-\frac{1}{2} & e_2e_3-e_0e_1 & R_y/2 \\ e_1e_3-e_0e_2 & e_2e_3+e_0e_1 & e_0^2+e_3^2-\frac{1}{2} & R_z/2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

X_i= i-th optimization variable,
i = 1-7 for the front door; i =8-14 for the rear door

OPTIMIZATION MODEL

Objective Function:

Figure 3 shows some possible measurement locations for the automobile door fit. The measurement points can be classified into three classes. The first class of points (Class I) are points whose gap and flush values are determined by the relative location of the *front door and the BIW* (points 1 - 8). The second class of points (Class II) are points whose gap and values are determined by the relative location of the *rear door and the BIW* (points 9 - 16). The third class of points (Class III) are points whose gap and flush are determined by the relative location of the *front and the rear door* (points 17 and 18).

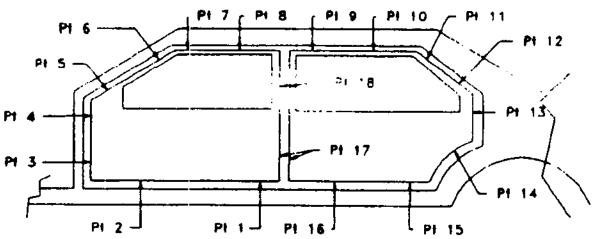

FIGURE 3: LOCATION OF MEASUREMENT POINTS

The vectors from the measurement point on the BIW to the corresponding measurement point on the door are:

$$B_j - T1(X_i) * D1_j \qquad (1a)$$

$$B_j - T2(X_i) * D2_j \qquad (1b)$$

$$T1(X_i) * D1_j - T2(X_i) * D2_j \qquad (1c)$$

where, j = the measurement point number;
i = 1,2,3,...14 (the variables to be optimized)

Equations (1a-c) are the vectors between the door and the body at each measurement point after the door has been placed into the door opening. The form of equation 1 depends on the type of point that is of interest. For example, if the point of interest is a Class I point (pt # 1-8), the proper equation would be equation 1a. On the other hand, if the point of interest is a Class II point (pt # 9-16), the proper equation would be equation 1b. Similarly, if the point of interest is a Class III point (pt # 17 & 18), the proper equation is equation 1c.

To get a true representation of the error in the fit, we need to project these vectors onto the vectors which define the gap and flush (figure 2). The vector that defines the direction of gap at point i is called GP_i. Similarly, the vector that defines the direction of the flush at point i is called FP_i. Therefore, the gap can be defined by the length of this projected vector. Symbolically this is written for the gap as:

$$\mathrm{Proj}\left(B_j - T1(X_i) * D1_j, GP_j\right) \qquad (2a)$$

$$\mathrm{Proj}\left(B_j - T2(X_i) * D2_j, GP_j\right) \qquad (2b)$$

$$\mathrm{Proj}\left(T1(X_i) * D1_j - T2(X_i) * D2_j, GP_j\right) \qquad (2c)$$

Similarly, for the flush as:

$$\mathrm{Proj}\left(B_j - T1(X_i) * D1_j, FP_j\right) \qquad (3a)$$

$$\mathrm{Proj}\left(B_j - T2(X_i) * D2_j, FP_j\right) \qquad (3b)$$

$$\mathrm{Proj}\left(T1(X_i) * D1_j - T2(X_i) * D2_j, FP_j\right) \qquad (3c)$$

Where, "proj(A,B)" is a function which calculates the length of projection the vector A onto B.

The gap and flush values that are calculated by using equations 2 and 3 yield the absolute gap and flush values. These values of gap and flush are the function of the optimization variables (X_i), that also determine the position of the doors in the BIW. To get the deviation from the design value at each measurement point these values of gap and flush can be subtracted from the design gap (DG_i) and flush (DF_i). If the deviation of the gap and flush from nominal are squared and summed for all the measurement points the optimization model objective function is:

$$\begin{aligned} \mathrm{Min}\, J(X_i) = {} & \sum_l \left\{ \begin{array}{l} W_{G_l}\left(\mathrm{proj}\,(B_l - T1(X_i) * D1_l, GP_l) - DG_l\right)^2 + \\ W_{F_l}\left(\mathrm{proj}\,(B_l - T1(X_i) * D1_l, FP_l) - DF_l\right)^2 \end{array} \right\} + \\ & \sum_j \left\{ \begin{array}{l} W_{G_j}\left(\mathrm{proj}\,(B_j - T2(X_i) * D2_j, GP_j) - DG_j\right)^2 + \\ W_{F_j}\left(\mathrm{proj}\,(B_j - T2(X_j) * D2_j, FP_j) - DF_j\right)^2 \end{array} \right\} + \\ & \sum_k \left\{ \begin{array}{l} W_{G_k}\left(\mathrm{proj}\,(T1(X_i) * D1_k - T2(X_i) * D2_k, GP_k) - DG_k\right)^2 + \\ W_{F_k}\left(\mathrm{proj}\,(T1(X_i) * D1_k - T2(X_i) * D2_k, FP_k) - DF_k\right)^2 \end{array} \right\} \end{aligned} \qquad (4)$$

where, l = 1 to No. of Class I Points
j = No. of Class I Points to No. of Class I & II Points
k = No. of Class I & II Points to Total No. of Points
DG_i = Design Gap at point i
DF_i = Design flush at point i

Constraints

The constraints of the optimization problem are derived from the geometry of the problem. There are three classes of constraints and within each constraint class there are multiple constraints. The three classes of constraints are euler parameter normalization constraints, minimum gap constraints, and minimum parallelism constraints

Euler Parameter Normalization Constraint. The Euler parameter constraint is included as a constraint to insure that the rotation of the door is valid, therefore, resulting in a homogeneous transformation. The relationship between the Euler Parameters must be:

$$e_0^2 + e_1^2 + e_2^2 + e_3^2 = 1$$

In the optimization routine however, this constraint is written as an inequality constraint to account for computer round-off errors. Hence, the constraint for the front door rotation is written as:

$$g_1: (X_1^2 + X_2^2 + X_3^2 + X_4^2 - 1) \le E$$

This constraint must also be included for the rear door to ensure that the rotation of the rear door is valid. Similarly, the Euler parameter constraint for the rear door is:

$$g_2: (X_8^2 + X_9^2 + X_{10}^2 + X_{11}^2 - 1) \le E$$

where, E is a small number and the X_i's in this case are the Euler parameters and optimization variables (X_1 - X_4 for the front door and X_8 - X_{11} for the rear door.)

Gap Constraint. The gap constraint is included in the model to allow the user some flexibility. The user has a choice in the usage of the gap constraint. Essentially, the gap constraint is added to the model to allow the user to specify a minimum allowable gap at a measurement point.

To develop the equation for the constraint, the vector from a measurement point on the body to the corresponding point on the door must be defined. This vector has been defined in equation 1.

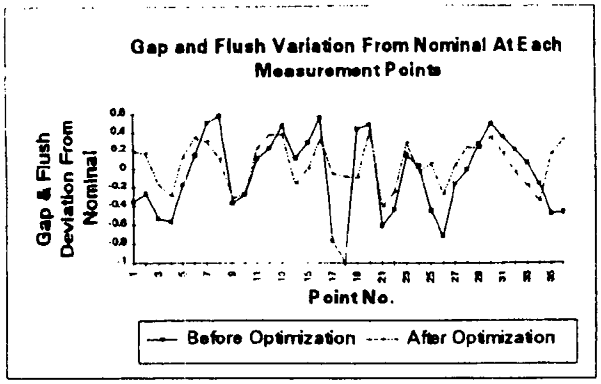

FIGURE 4: GAP AND FLUSH VALUES BEFORE AND AFTER OPTIMIZATION

TABLE 1: STATISTICAL RESULT OF THE CASE STUDY

	Gap & Flush Variation	Gap Range	Flush Range
W/O Optim.	2.5952	1.5989	2.3741
With Optim.	1.4681	0.6972	1.5203

* All units in mm

In the previous example the weighting factors were all set equally. That is, the importance of each gap and flush in the optimization was equal. Also, there were no minimum gap and minimum parallelism constraints used in the optimization.

To further demonstrate the capabilities of the optimization scheme, the same CAD generated data was used for generating 50 replications of the optimization described above. For each replication the random deviation on the order witnessed in automobile plants ($6\sigma = 2$ mm) is added to each point. With each replication the optimum solution is found and the within car variation before and after optimization is calculated and plotted in figure 5.

For comparison, the plot of the before and after optimization within car gap and flush variation for the 50 samples is shown in figure 5. From the plot one can see that in every case the within car gap and flush variation was reduced. On average the variation was reduced by 0.69 mm. A summary of some of the optimization parameters of interest are shown in table 2.

As can be seen in figure 5 and table 2, the variation and the ranges have been reduced. This reduction will result in a door fit that is more aesthetically pleasing to the customer as well as increasing the functionality of the door.

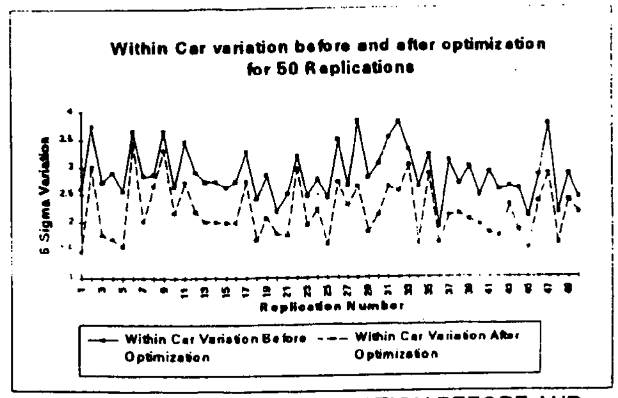

FIGURE 5: WITHIN CAR VARIATION BEFORE AND AFTER OPTIMIZATION

TABLE 2: SUMMARY OF THE OPTIMIZATION SIMULATION

Reduction in:	
Gap and Flush 6σ	0.69 mm
Gap 6σ	0.59 mm
Gap Range	0.41 mm
Flush 6σ	0.69 mm
Flush Range	0.45 mm

SENSITIVITY ANALYSIS:

In the model description above, two classes of constraints are introduced. These constraints (Minimum Gap and Minimum Parallelism) are used only when the user chooses to use them. This raises the question of how these constraints affect the optimization. To determine this answer analytically would be very difficult due to the non linearity and the shear size of the problem. As a consequence, we have chosen to do a sensitivity analysis of two classes of constraints using an experimental approach. In each sensitivity analysis conducted the data from the case study is used. The optimization is then conducted with the appropriate constraint used. The constraint value is then varied over a range and the optimum solution is found and compared to the optimum solution without any constraints.

In the case study presented previously, the optimum location of the panels yielded a gap and flush variation of 1.46 mm. It can be seen from figure 6 that, when a gap constraint is used, the optimum gap and flush variation varies from the unconstrained optimum value of 1.46 mm to over 4 mm. When the minimum gap constraint value is relatively small the optimum gap and flush variation is found to be the same as the case when no gap constraint is used. However, when the value of the minimum gap is increased, the optimum value of the gap and flush increases accordingly. Otherwise stated, as the minimum gap constraint value increases, the minimum gap constraint becomes active.

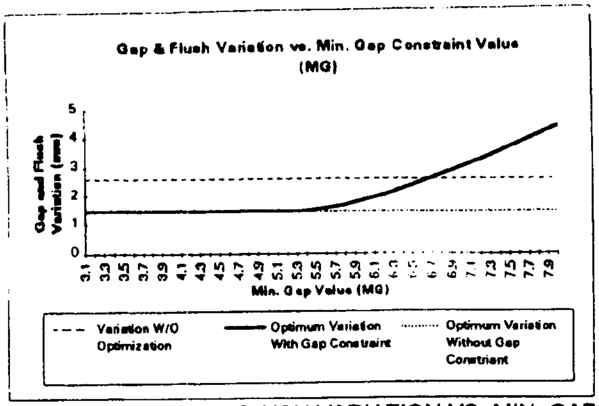

FIGURE 6: GAP AND FLUSH VARIATION VS. MIN. GAP VALUE

Similarly, figure 7, when a minimum parallelism constraint is used, the optimum gap and flush variation varies from the unconstrained optimum value of 1.46 mm to over 1.5 mm. When the minimum parallelism constraint value is relatively small the optimum gap and flush variation is found to be the larger than the case when no gap constraint is used. However, when the value of the minimum gap is increased, the optimum value of the gap and flush decreases to the unconstrained value of 1.46 mm.

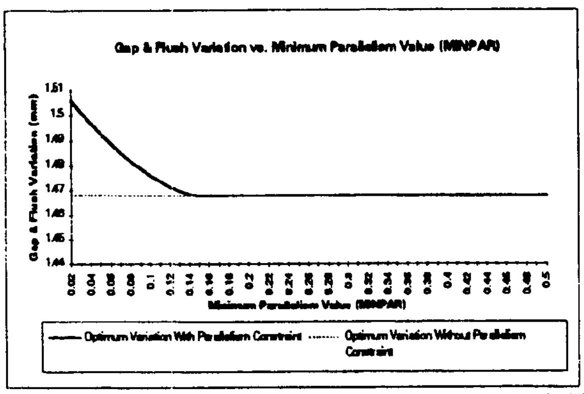

FIGURE 7: GAP AND FLUSH VARIATION VS. MINIMUM PARALLELISM VALUE

CONCLUSIONS

The panel fitting problem was formulated into a constrained optimization problem. The objective of the optimization is to determine the position of automobile panels in the body opening such that the within-car variation of the gap and flush is minimized. The constraints in the optimization model include: (1) Euler parameter constraints; (2) minimum gap constraints; and (3) minimum parallelism constraints. Simulations were conducted to evaluate the effect of the optimal fitting on the door fit. Based on these simulations, the following observations can be made:

1. The gap and flush variation is reduced by the optimization. Based on the 50 simulated door fits presented, the optimization algorithm reduced the within-car variation in the gap and flush on average by 24.3% in 50 simulated door fits and by as much as 43.43% in the case study presented in this paper. As a result, the door fit quality is improved both aesthetically and functionally.
2. From the 50 simulations presented, it can be seen that the optimization algorithm found the optimal position that reduced the variation in every case, which illustrates the robustness of the optimization algorithm.

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