Multivariate Analysis and Evaluation of Adaptive Sheet Metal Assembly Systems

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Abstract:

The flexibility of sheet metal assembly processes is one of the most critical issues in the design stage of assembly systems. Currently in the automotive industry, flexibility and adaptability of assembly systems are mainly considered as the capability to assemble a family of products. The notion of assembly system flexibility, as understood from the point of view of error compensation by upstream processes, has not been widely researched. This paper presents a systematic method of flexible/adaptive assembly system evaluation, based on its ability to compensate for part dimensional variability caused by upstream processes. This allows for the expansion of the present design for manufacturability approaches by applying multivariate analysis and fixture diagnostic techniques. The proposed method was applied to evaluate a flexible assembly system at a US manufacturing plant.

Keywords: Flexible assembly, error compensation, dimensional error

1. Introduction:

Ongoing developments in the field of flexible/adaptive assembly technology have resulted in the automation of increasingly complex assembly processes such as sheet metal assembly. Moreover, traditional application of flexible assembly systems for middle range production volume and product complexity (Makino and Arai, 1994) has expanded to application in high volume production, thus increasing the demands on assembly systems, including tighter assembly tolerances and growing number of component variants. Currently, many of the problems being encountered in automotive sheet metal assembly stem from the fact that the products were designed with a shallow understanding of assembly processes, and that the assembly tooling was designed with a lack of knowledge about product variability. In order to achieve a reliable assembly process and a high degree of assembly quality, it is necessary to examine the automation-related design of both product and process in the earliest phases of product and tooling design (Kroll et al., 1988). Until now significant results were achieved in the area of integrating product and processes during design phase through DFA/DFM (Boothroyd; Miyakawa et al., 1990), design for producibility (Suh, 1988), assembly-oriented design (Warnecke and Bassler, 1988; Milberg and Diess, 1988), feature-based design, and others.

Currently in the automotive industry, the areas of flexibility and adaptability of assembly systems are mainly addressed as the capability to assemble a family of products by using statically and dynamically reconfigured systems (Makino and Arai, 1994). The notion of assembly system flexibility, understood as error compensation caused by upstream processes, has not been widely researched. The current DFA/DFM approaches do not emphasize the impact of incoming part variability on the design of flexible assembly systems (Warnecke and Bassler, 1988). However, the importance of the product error compensation in flexible assembly systems has been observed by a few researchers (Arai and Takeuchi, 1992; Reinhart et al., 1996). Reinhart et al. (1996) emphasized the importance of minimizing scatter in the performance and fault characteristics of an assembly system. Arai and Takeuchi (1992) suggested to use "adjustable assembly" or "selective assembly" in order to assemble a product with high accuracy using parts manufactured with limited accuracy.

This paper presents a systematic method of flexible assembly system evaluation during the design phase, based on its ability to compensate for part dimensional variability caused by upstream manufacturing processes. This allows for the expansion of the present *design for manufacturability* approaches by applying multivariate analysis to model dimensional faults (variation patterns) of product based on the CAD design information. The proposed methodology is based on three steps presented in three consecutive sections of the paper: (1) modeling of variation patterns of pre-assembled parts and subassemblies (components); (2) modeling of assembly system capability to compensate for components error; and (3) evaluation of assembly system capability to compensate for pre-assembled component variability (Fig. 1). The methodology is applied to sheet metal assembly of door and automotive body using Net Form and Pierce (NF&P) system (Fig. 2; layer 3). The NF&P system has the ability to compensate for position and orientation errors of the door and door openings during assembly process to minimize door-to-body gap variation.

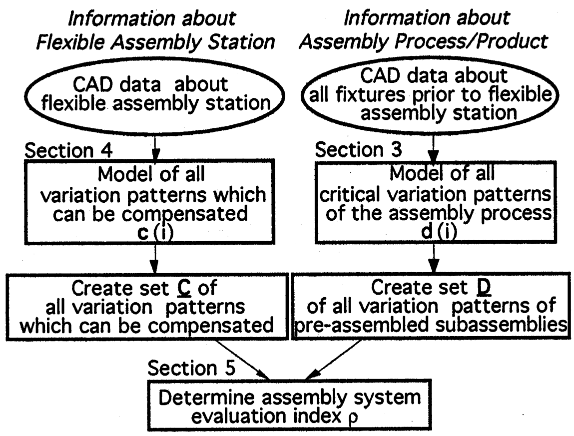


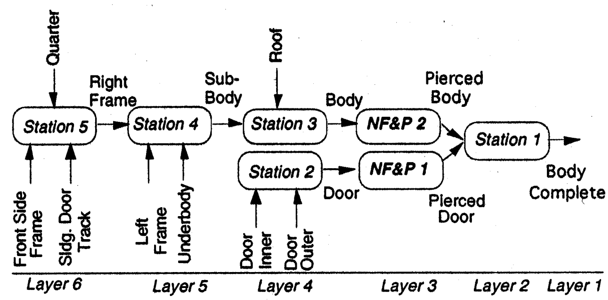
Figure 1. Outline of the methodology

2. Automotive body assembly system with and without error compensation

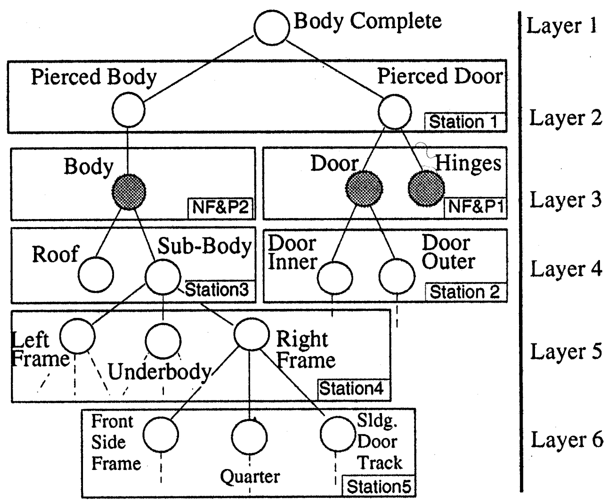
An automotive body assembly system is a multi-fixture hierarchical system with over 200 stations/fixtures. Sheet metal components are joined together at each station to form higher layer subassemblies, which then become input components for the next layer of the assembly (Fig. 2b).

Study on the automotive assembly process indicate that as many as 72% of all root causes of faults are attributable to failures of assembly fixtures (Ceglarek and Shi, 1995). The largest identifiable portion of all assembly fixture failures is attributable to process variability, which takes the form of dimensional variation of the product. Thus, one of the principal quality/productivity parameters for sheet metal assembly process is dimensional variation of the final product (body with installed doors).

Traditional automotive assembly systems are designed without error compensation capabilities. Each station fixture uses a fixed set of locators to position each part independently from the other using, for example, a 3-2-1 fixture layout principle. This means, that errors from each station can accumulate for over long and complex assembly lines. Since not all dimensional variations are of equal importance for overall performance of the vehicle, the compensation of errors in critical stations can significantly improve the final quality of the product.



(a) Assembly process layout



(b) Hierarchical assembly process

Figure 2. An automotive Body Assembly Process.

In the case of automotive body assembly process, closure panel fit-to-body is one such critical station. The recent application of the so called NF&P stations is an example. The NF&P station tries to compensate for error in the body (or closure panels) by piercing door-to-body installation holes in relation to selected critical points used as compensating locators (Fig. 3). The compensating locators on the body and doors are intended to compensate for the accumulation of all errors which occurred in the station prior to the NF&P (Fig. 2b). The selection of compensating locators is based on the key product or process characteristics used for inspection of the final vehicle.

The correctly designed NF&P system needs to compensate for errors consisting of variation patterns which occurred during upstream assembly process, that cause deterioration of quality by increasing the dimensional variation of the final product. This can be accomplished by identifying, modeling, and compensating critical errors consisting of variation patterns which affect the final quality of the product. Optimally designed NF&P systems should compensate for the most critical variation patterns caused by the assembly system.

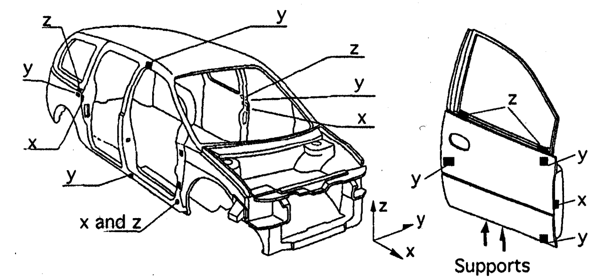


Figure 3. Layout of compensation points

3. Modeling of Pre-assembled Component Variation Patterns

The variation patterns of the pre-assembled components, and the compensation capability of the assembly system, are modeled using a fixture locator layout geometry (CAD data) and a multivariate statistical approach, such as the Principal Component Analysis. In this approach, the variation patterns for each component caused by failure of fixture locators are defined as eigenvalue/eigenvector pairs.

The most common fixture layout is *3-2-1* principle, which locates part by three groups of locators (Tooling Elements—TEs), laid out in two orthogonal planes. As shown in Fig. 4, these three groups usually include: (1) a four-way pin P_1 to precisely position the part in two directions (X and Z) on the first plane, (2) a two-way pin P_2 or NC block to locate the part in one direction (Z) laid on the first plane, and (3) all remaining locators (C_1, C_2 and C_3) to locate the part on the second plane. Therefore, a six-fault system, related to six degrees of freedom, constitutes a complete set of potential root causes of the dimensional faults in the fixture. Each TE controls a part in the defined direction (control axis). For example, the Z axis is the control axis of the locating pin P_2 (Fig. 4). Furthermore, each locator TE is associated with either none, one or more so called complement tooling element(s) (CTEs) defined as any locator(s) in the fixture, except TE, which control part in the same direction as locator TE. For example, if TE≡P_1 controls part in Z direction, the CTE≡P_2 (the only other locator beyond TE which control component in Z direction).

Dimensional faults caused by TE failures manifest themselves in specific pre-determined variation patterns: (1) translation along the control axis; if the number of CTEs, n_{CTE}=0, (for example, type-2 pattern, failure of P_1 in X axis, Figs. 4 and 5); (2) rotation along the axis defined by one CTE, if the number of CTEs, is n_{CTE}= 1 (for example, type-3 pattern—failure of TE≡P_2; one CTE≡P_1; Fig. 5); and (3) rotation along the axis defined by two CTEs, if the number of CTEs to a faulted TE is n_{CTE}=2 (for example, type-4 pattern—failure of TE≡C_1; two CTEs— C_2 and C_3; Fig. 5).

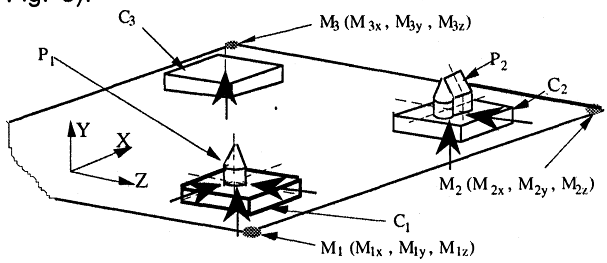


Figure 4. A 3-2-1 fixture layout

Variation pattern model based on CAD information. The manifestations of the TE faults are represented by measurement points $M_i(M_{ix}, M_{iy}, M_{iz})$ and their standard deviations $\sigma_i(\sigma_{ix}, \sigma_{iy}, \sigma_{iz})$, i=1,2,3 (Fig. 4). The magnitude of dimensional variation captured by sensor i (σ_i) depends on the severity of the fault described by the standard deviation of the TE, σ_{TE}^{F}, and on the geometrical relations between the location of the sensors and the TEs. These relations can be summarized as: $\sigma_{TE}^{F} = k_i\ \sigma_i$ (Ceglarek and Shi, 1996). For type-1, -2, and -3 faults these relations can be expressed as:

$$\frac{\sigma_{TE}^{F}}{d(\mathrm{TE},\mathrm{CTE})} = \frac{\sigma_i}{d(\mathrm{CTE},\mathrm{M_i})} \qquad (1)$$

where TE describes faulty locator (Fig. 5), i.e., P_1 for type-1 pattern; *d*(TE, CTE) describes distance between TE and CTE (for type-1 pattern—P_1 and P_2); and *d*(CTE, M_i) describes distance between CTE and measurement point M_i. In case of variation patterns described by type-4, -5, and -6 faults the following relation holds:

$$\frac{\sigma_{TE}^{F}}{d(\mathrm{TE},\mathrm{axis}_{CTE1\text{-}2})} = \frac{\sigma_i}{d(\mathrm{axis}_{CTE1\text{-}2},\mathrm{M_i})} \qquad (2)$$

where TE is a faulty locator (C_1 in type-4 fault); $\mathrm{axis}_{CTE1\text{-}2}$ describes the axis going through the two CTEs in the fixture (locators C_2 and C_3 in type-4 fault); *d*(TE, $\mathrm{axis}_{CTE1\text{-}2}$) is a distance between TE and $\mathrm{axis}_{CTE1\text{-}2}$; similarly *d*($\mathrm{axis}_{CTE1\text{-}2}$, M_i) is a distance between $\mathrm{axis}_{CTE1\text{-}2}$ and M_i.

The variation pattern model of the *3-2-1* fixture layout describes the part variation patterns in terms of the TE's and the measurement points layout (M_i). A total of nine measurement variables χ_j, j=1, 9 (3 sensors, each measuring three axes) are used to describe the *3-2-1* fixture. The model of the variation patterns for the *3-2-1* fixture is described by a matrix of fixture variation patterns

$$\mathbf{D} = (\mathbf{d}(1), \ldots, \mathbf{d}(6)) \qquad (3)$$

where $\mathbf{d}(i) = (d_{1i}, \ldots, d_{ni})^T$ is a vector describing a type-i pattern (Fig. 5), with n (=9) entries corresponding to the measured variables χ_j: $d_{ji} = \sigma_{\chi_j}/\sigma$, j=1, ..., n, where σ_{χ_j} is the standard deviation of variable χ_j, and $\sigma = \sqrt{\sum_{j=1}^{n} \sigma_{\chi_j}^2}$ (Ceglarek and Shi, 1996).

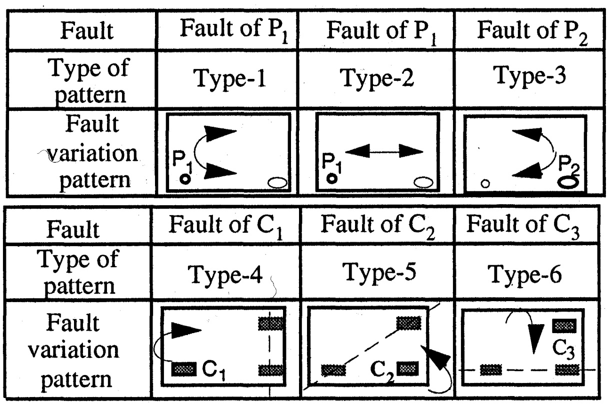


Figure 5. Variation patterns of 3-2-1 fixture

Variation patterns model based on statistical representation. In production stage these variation patterns can be extracted from the measurement data. The variation patterns can be described by multisensor data using a multivariate statistical approach, Principal Component Analysis (PCA) (Ceglarek and Shi, 1996). PCA describes a variation pattern by finding p≤n linear transformations of n variables. Each variable represents measurement data from one of three measurement points/sensors (M_1, M_2 and M_3) in one axis (X, Y or Z), i.e., n=9. Eigenvectors $\mathbf{a}_i^T = (a_{i1}, \ldots, a_{i9})$, obtained from the data covariance matrix, represent variation pattern. Geometrically, the first eigenvector points in the direction of the greatest variability in the data, and the orthogonal projection of the data onto this eigenvector is the first eigenvalue.

The dominant eigenvector ($\mathbf{a}_1$) of the variation pattern, described by the TE failure and obtained from the measurement data, is equal to the diagnostic vector $\mathbf{d}$(i) describing the failure of this TE and obtained based on the fixture CAD geometry.

Set of matrices of selected fixture variation patterns. Having developed a matrix of fixture variation patterns **D**, a set of matrices can be developed for selected fixtures which should be compensated by flexible/ adaptive assembly station such as NF&P. This set can be defined as:

$$\underline{\mathbf{D}} = \{\mathbf{D}_1, \mathbf{D}_2, \ldots, \mathbf{D}_i, \ldots, \mathbf{D}_{nd}\} = \bigcup_{j=1}^{n_d} \left(\bigcup_{i=1}^{m} \mathbf{d}_j(i) \right) \qquad (4)$$

where m is a number of patterns within one fixture/station, n_d is a number of fixtures/stations for which errors need to be compensated, and $\mathbf{D}_i$ is a matrix with all variation patterns to be compensated in station/fixture i.

The identification and selection of variation patterns for compensation can be based on either technical aspects such as vehicle performance (wind noise, water leak, or closing effort, which are caused by dimensional variations of the parts and subassemblies), downstream assembly processes (difficulty with downstream assembly operations due to part misalignment or interferences caused by upstream operations), or non-technical issues such as customer perception and requirements.

4. Modeling of Assembly System Part Error Compensation Capability

Each flexible assembly station such as NF&P has the capability to compensate for some dimensional errors (variation patterns). Similar to section 3, compensation matrix will be defined with all variation patterns which can be compensated by the flexible station (NF&P):

$$\mathbf{C} = (\mathbf{c}(1), \ldots, \mathbf{c}(i), \ldots, \mathbf{c}(n_c)) \qquad (5)$$

where $\mathbf{c}$(i) is a variation pattern vector which can be compensated by the adaptive station, and n_c is a total number of variation patterns which can be compensated by the station. For example, in the case of the NF&P station (Fig. 3), all variation patterns which were caused by errors in upstream stations 4 and 5 should be compensated (see Section 6).

5. Assembly System Evaluation Index ρ

The final evaluation of an assembly system for its ability to compensate for pre-assembled component variability is defined by the index ρ. The index is described as a quotient of the product of two sets: (a) the set of variation patterns of pre-assembled component, and (b) the set of variation patterns which can be compensated by the assembly system. Thus, the evaluation of the assembly system is performed as a comparison between the pre-assembled component variation patterns and compensated variation patterns.

The evaluation is conducted in four steps:

(1) model each variation pattern **d**(i) (based on the CAD information about fixture layout geometry or directly based on the production data) and use it to create a set of variation patterns $\underline{\mathbf{D}}$;

(2) model each variation pattern **c**(i) that can be compensated by the adaptive station and create a set of compensated patterns $\underline{\mathbf{C}}$;

(3) select exclusive pairs of variation patterns (**d**(i), **c**(j)) such that

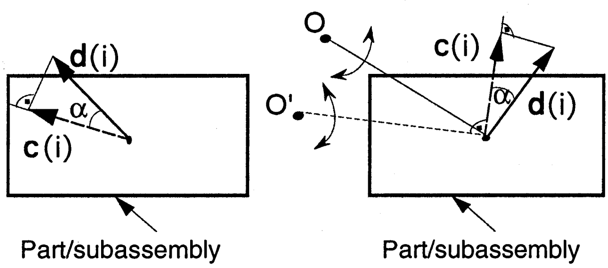
$$\mathbf{card}(\underline{\mathbf{D}} \cap \underline{\mathbf{C}}) = \sum_{i,j=1}^{n_{all},n_c} \mathbf{card}(d(i) \cap c(j)) = \max \quad (6)$$

where n_{all} and n_c are the numbers of all critical and compensated patterns respectively, $\mathbf{card}(\underline{\mathbf{D}})$ is a cardinality of set $\underline{\mathbf{D}}$, $\mathbf{card}(\mathbf{d}(i) \cap \mathbf{c}(j)) = \cos\alpha$, where α is an angle between vectors **d**(i) and **c**(j) (Fig. 6), and $\mathbf{card}(\mathbf{d}(i) \cap \mathbf{d}(i)) = 1$;

(4) determine assembly system evaluation index

$$\rho = \frac{\mathbf{card}(\underline{\mathbf{D}} \cap \underline{\mathbf{C}})}{\mathbf{card}(\underline{\mathbf{D}})} \quad (7)$$

The index represents the relative number of variation patterns which can be compensated in relation to pre-defined patterns.



(a) translational pattern (b) rotational pattern

Figure 6. Variation patterns: **d**(i) and **c**(i)

The proposed evaluation method can be conducted in three different stages of the product development cycle: (1) during the concept design of a new flexible assembly system, using exclusively CAD information about fixture design and/or by using production measurement data from the previous product model; (2) during the detailed design stage of a new flexible assembly system, using variation simulation analysis (VSA); and (3) during the production stage, using current production data.

6. Implementation

An example of compensation of variation patterns caused by faults in the upstream fixtures is presented based on the automotive body assembly process and application of the NF&P stations.

As shown in Fig. 2b, an NF&P station is installed to compensate errors of the final fit of doors-to-body caused by the dimensional errors of (1) door or body itself (layer 4) and (2) frame subassembly process (layers 5 and 6) (Fig. 2b).

The set of variation patterns selected based on the final vehicle design requirements and customer perception can be presented as:

(1) Parallelism variation within pillars (A, B, C).

(2) Average gap variation within pillars (A,B,C).

(3) Average gap variation between pillars (a) (A gap) – (B gap) and (b) (B gap) – (C gap)

(4) Body-to-door flushness variation.

This can be translated to a set of critical variation patterns as shown in Fig. 7.

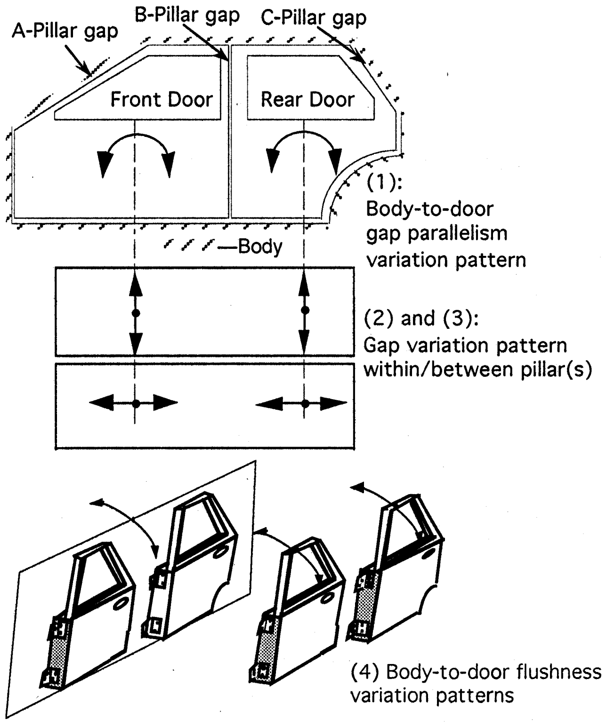


Figure 7. Variation patterns—design requirements

These variation patterns can be directly transferred to the set $\underline{\mathbf{D}}$ of critical variation patterns caused by the upstream faults of the fixtures.

Fig. 8 shows example of some of the variation patterns caused by faults in station 5 (Fig. 2b). The variation pattern can be modeled following the method presented in Section 3. These patterns can be modeled directly from the fixture layout CAD data. For the sake of simplicity, patterns caused by faults of the other upstream processes (stations 2, 3 and 4) are not shown in this paper.

From Fig. 8 $\mathbf{card}(\underline{\mathbf{D}})=7$, where $\underline{\mathbf{D}}=\{\mathbf{d}(i)\}$ for i=1, ...7. The NF&P adaptive system (Fig. 3) compensation capability are directly related to the layout of compensating locators. For the layout presented in Fig. 3, the NF&P can compensate for: (1) both doors up/down variation pattern (**d**(1)), (2) both doors fore/aft variation pattern ($\mathbf{d}(3)$), and (3) both doors flushness variation pattern ($\mathbf{d}(5)$). Therefore, NF&P can compensate the following variation patterns $\underline{C}=\{\mathbf{d}(1), \mathbf{d}(3), \mathbf{d}(5)\}$, and $\mathbf{card}(\underline{C} \cap \underline{D})=3$. Finally from Eq. (7), we obtain that $\rho = 0.43$. The evaluation index can help during designing adaptive system, as well as during designing the other subassembly processes, to minimize the final variation of the product. It can be used as a benchmarking or analytical tool to optimize variation propagation for the most critical areas of the final product.

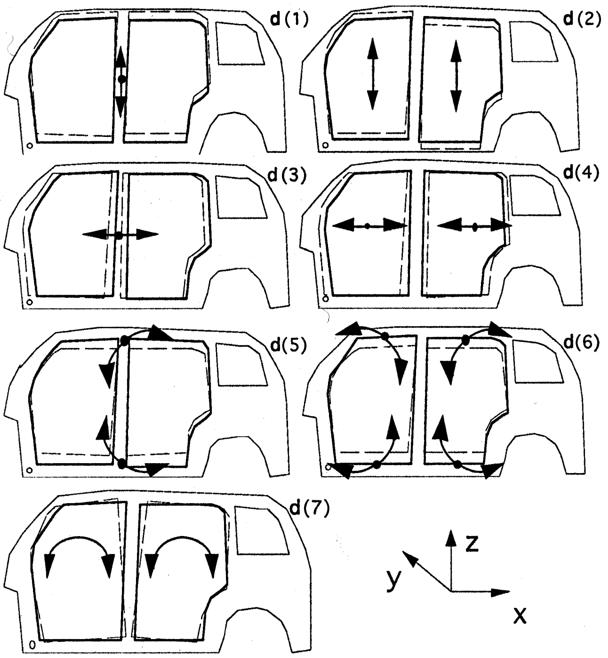


Figure 8. Variation patterns— upstream processes

7. Conclusions

Flexibility and adaptability of the sheet metal assembly products and processes are two of the most critical issues in the design stage of assembly systems. Currently, however, flexibility of assembly systems is mainly addressed as the capability to assemble a family of products by using statically and dynamically reconfigurable systems. The notion of assembly system flexibility, as understood from the point of view of error compensation caused by upstream processes, has not been widely researched.

This paper presents a systematic evaluation method of flexible assembly system during the design phase, based on its ability to compensate part dimensional variability caused by upstream manufacturing processes. This expands methods by considering manufacturability issues using multivariate statistical analysis and fixture diagnosis approaches. The proposed method is based on (1) modeling variation patterns (faults) of pre-assembled components; (2) modeling flexible assembly system capability to compensate component error; and (3) evaluation of assembly system capability to compensate for pre-assembled component variability. The results of this methodology are summarized in the form of assembly system evaluation index.

The developed approach has been successfully applied to evaluate assembly system currently being used at one of the U.S. automotive manufacturer.

Acknowledgment

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