Contributions to Multi-stage Assembly Systems

Prof. Hu pioneered the research area of compliant, non-rigid part assembly by developing the “Stream of Variation” theory for predicting and diagnosing quality variation in multi-stage assembly systems [1]. Prior approaches for assembly quality control were based on univariate, sampled-data which did not take into consideration the relationships among various quality features measured on an assembly. With multivariate data made available by the coordinate measurement machines and in-line vision systems, Dr. Hu first introduced Principal Component Analysis (PCA) to the diagnosis of quality variation in such multi-stage assembly systems [2]. Measurements from multiple locations on the assembly are clustered together according to the correlation among them and the clusters are compared with the assembly hierarchy. Then the patterns of assembly variation for each clustered group of locations are identified and displayed based on the variance of the principal components and their eigenvectors. This represents a scientifically sound yet physically intuitive way of explaining assembly variation. Perceptron, Inc. {https://perceptron.com/solutions/automated-metrology} incorporated the multi-variate analysis and PCA algorithm into its software offering for automotive in-line metrology.

From the variation patterns, the root causes of variation are then systematically identified and removed. The application of PCA and associated methodologies helped the U.S. auto manufacturers significantly reduce auto body dimensional variation and shorten launch time. Under a grant from the NIST Advanced Technology Program, "2 mm Program - Development of Advanced Systems and Technologies for Controlling Dimensional Variation in Automobile Body Manufacturing" (1992 – 1996), Dr. Hu and his team worked closely with Chrysler, General Motors and several automotive suppliers in successfully implementing the systematic methodology in the automobile assembly plants**.** See figure 2 as an example of the reduction of variation in an assembly plant.

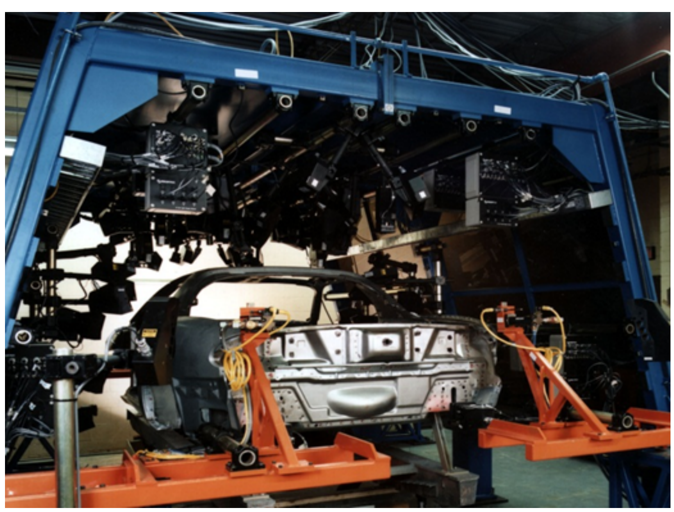

Figure 1. In-line machine vision system measuring a car body.

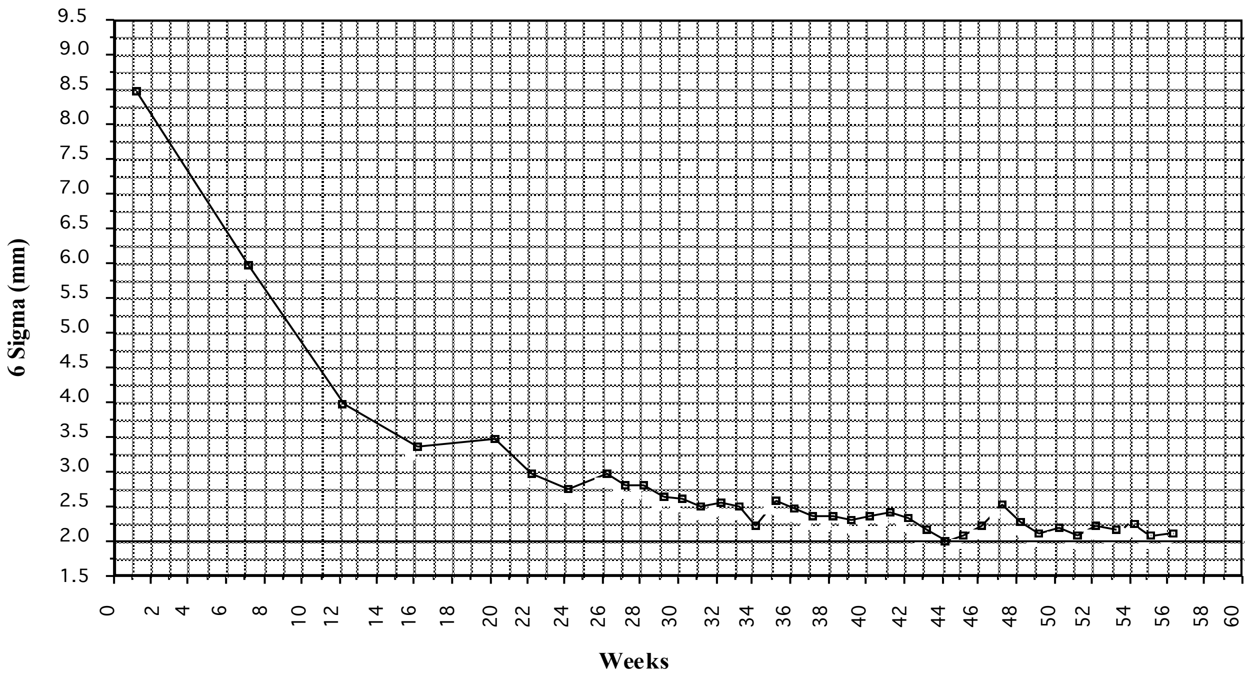

Figure 2. Reduction of auto-body assembly variation

Independent retrospective study of the ATP project by researchers from MIT summarize the economic impact of project {See section on Auto Body Manufacturing Assembly, page 22 – 23. https://www.yumpu.com/en/document/read/29341397/overall-project-performance-nist-advanced-technology-program}. NIST estimates that it increased the U.S. gross domestic product by $186 million.

To move the variation reduction efforts upstream to design, Prof. Hu and his students developed new models for predicting the propagation of variation in multi-stage compliant assembly systems by innovatively fusing engineering structural analysis with advanced statistics [3, 4, 5]. Existing methods for predicting assembly variation before 1992 were based on the assumption of rigid bodies. But sheet metal parts can deform during assembly when subjected to clamping and welding due to part non-rigidity. These deformations and subsequent spring back after releasing the clamps and weld machines cause dimensional changes, making rigid body based variation analysis invalid for sheet metal parts. Thus, Prof. Hu and his students developed a generalized method for variation analysis of non-rigid part assembly by combining finite element analyses with multivariate statistics. Using finite element analysis, a mechanistic model was established to relate the assembly deformation to component variation. Then multivariate statistical method was applied to the mechanistic model to calculate assembly variation [3, 4, 5]. Finally, both station level and system level models were developed. His paper on "Modeling Variation Propagation of Multi-Station Assembly Systems with Compliant Parts" [6] won the best paper award in the 2001 ASME Design for Manufacturing Conference for its original contribution.

Hu also successfully extended the methods of compliant assembly to performance modeling of electronic packaging and fuel cell assembly [7, 8, 9].

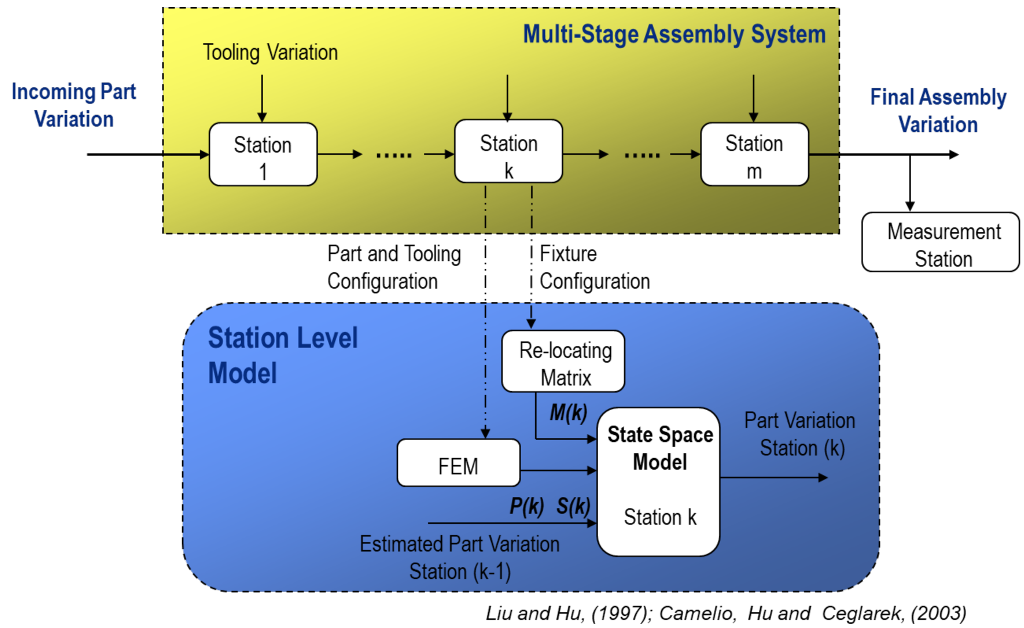

Figure 3. Modeling of multi-stage assembly system with non-rigid parts.

Selected Publications

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1. SJ Hu, (1997), "Stream-of-variation theory for automotive body assembly", *CIRP Annals-Manufacturing Technology* 46 (1), 1-6.

2. SJ Hu, SM Wu, (1992),"Identifying sources of variation in automobile body assembly using principal component analysis", *Transactions of NAMRI/SME* 20, 311-316

3. SC Liu, SJ Hu, TC Woo, (1996), "Tolerance analysis for sheet metal assemblies", *ASME Journal of Mechanical Design* 118, 62-67.

4. SC Liu, SJ Hu, (1997), "Variation simulation for deformable sheet metal assemblies using finite element methods", *ASME Journal of Manufacturing Science and Engineering*, 119, 368-374

5. W Cai, SJ Hu, JX Yuan, (1996), "A variational method of robust fixture configuration design for 3-D workpieces", *ASME Journal of Manufacturing Science and Engineering* 119, 593 – 602.

6. J Camelio, SJ Hu, D Ceglarek, "Modeling variation propagation of multi-station assembly systems with compliant parts", ASME Journal of Mechanical Design 125, 673-681.

7. M Chin, KA Iyer, SJ Hu, (2004), "Prediction of electrical contact resistance for anisotropic conductive adhesive assemblies", *IEEE Transactions on Components and Packaging Technologies*, 27 (2), 317-326.

8. L Zhang, Y Liu, H Song, S Wang, Y Zhou, SJ Hu, (2006), "Estimation of contact resistance in proton exchange membrane fuel cells", *Journal of Power Sources* 162 (2), 1165-1171.

9. Y Zhou, G Lin, AJ Shih, SJ Hu, (2007) "A micro-scale model for predicting contact resistance between bipolar plate and gas diffusion layer in PEM fuel cells", *Journal of Power Sources* 163 (2), 777-783.