

**Assembling Technique Based on the Statistical Feed-Forward Control Model
for Low Precision Manufacturing Processes**

Von der Fakultät für Maschinenbau
der Technischen Universität Carolo-Wilhelmina zu Braunschweig

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ERKLÄRUNG

Hiermit erkläre ich, dass ich die vorliegende Arbeit - mit Ausnahme der in ihr ausdrücklich genannten Hilfen - selbständig verfasst habe.

Carlos Hernández

ZUSAMMENFASSUNG

Die Beiträge dieser Arbeit zum Ingenieurwissen sind das hier vorgestellte *Statistical Feed-Forward Control Model* (SFFCM) als Kern einer innovativen Montage-Technik und die *Statistical Dynamic Specifications Method* (SDSM), um dynamische Spezifikationen und Toleranzen zu verwalten.

Die Montage von Komponenten aus Fertigungsprozessen gekennzeichnet durch hohe Maßabweichungen wurde traditionell aus zwei unterscheidbaren Perspektiven betrachtet: die selektive und die adaptive Montage. Moderne Techniken aber verwenden in der Regel eine Kombination dieser Ansätze. Der größte Nachteil der selektiven Montagetechniken ist die Notwendigkeit zum Inspizieren von 100% der Elemente, so dass sie klassifiziert und anschließend zusammengebaut werden können. Die adaptiven Montagetechniken berücksichtigen in der Regel nicht die Evolution der Variation über die Zeit sondern nur die zuletzt untersuchte Probe, um die vorzunehmenden Anpassungen abzuschätzen. Keiner dieser Ansätze betrachtet die Variation als eine Überlagerung verschiedener Variationsarten.

Diese Arbeit nimmt die Herausforderung an, eine neuen Montage-Technik zu entwickeln, um die Herstellung von Baugruppen geringer Variation durch Paarung von Komponenten hoher Variation zu erreichen. Die wichtigsten Ergebnisse des vorgeschlagenen Modells sind die Reduzierung der resultierenden Variation, die Reduzierung der Ausschussrate und die Verbesserung der Prozessfähigkeits-Indizes.

Mit Hilfe der speziell entwickelten *Dynamic Assembling Simulation Software* (DASS) wurde eine große Reihe von Experimenten entwickelt, um die Produktion von vielen 1.000 Tsd. Baugruppen aus zwei Komponenten hoher Variation zu simulieren, so dass die einzelnen und kombinierten Einflüsse verschiedener die Produktion betreffender Faktoren ausgewertet werden können.

Die Simulationsergebnisse zeigten, im Vergleich zur vollständig randomisierten Montage, eine durchschnittliche Reduktion des verschobenen Erwartungswerts um 89% (von einem Mittelwert 29.55 mm zu einem verbesserten Mittelwert 29.95 mm bei einem nominellen Zielwert von 30.00 mm), eine durchschnittliche Reduktion der Standardabweichung um 14% (von 0.29 auf 0.25), eine durchschnittliche Verbesserung des Prozessfähigkeitsindex c_p des Montageprozesses um 16% (von 1.15 auf 1.34), eine durchschnittliche Verbesserung des Prozessfähigkeitsindex c_{pk} des Montageprozesses um 101% (von 0.63 auf 1.27) und eine

durchschnittliche Reduktion der Elemente außerhalb der Toleranz um 100% (von 28.6 pro tausend Paarungen auf Null).

Im Ergebnis trägt die vorgeschlagene SFFCM-basierte Montagetechnik, eine Kombination des adaptiven und selektiven Ansatzes mit Schwerpunkt auf der Inspektionsoptimierung, wirksam dazu bei, die Hauptziele dieser Arbeit zu erreichen: reduzieren der Prozessvariation, reduzieren der Ausschussrate und verbessern der Prozessfähigkeitsindizes. Zusammengefasst ist es möglich, mit Komponenten hoher Streuung zu Baugruppen mit geringer Maßabweichung zu gelangen. Aus einer anderen Perspektive betrachtet wurde ein fähiger Prozess ($c_p > 1.33$) durch die Kombination zweier nicht fähiger Teilprozesse erreicht.

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Assembling Technique Based on the Statistical Feed-Forward Control Model
for Low Precision Manufacturing Processes

by
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at the
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ABSTRACT

The contributions of this thesis to engineering knowledge are the Statistical Feed-Forward Control Model (SFFCM) as the core of the novel assembling technique proposed here and the Statistical Dynamic Specifications Method (SDSM) to manage dynamically targets and tolerances.

The assembly of components coming from manufacturing processes characterized by high dimensional variation has been traditionally approached from two distinguishable perspectives: selective and adaptive assembling. Modern techniques, however, usually adopt a combination of these approaches. The mayor downside of the selective assembling techniques is the need for inspecting 100% of the component items so that they can be classified to be assembled afterwards. The adaptive assembling techniques usually do not consider the evolution of the variation over time and only take into account the last inspected sample to estimate the adjustments that have to be made. None of these approaches consider the nature of the variation as a superposition of different variation forms.

This thesis embraces the challenge of developing a new assembling technique to deal with the problem of producing low variation assemblies by means of mating high variation components. The main objectives of the proposed model are the reduction of the resulting variation, the reduction of the scrap levels and the improvement of the process capability indices.

With the help of the specially developed Dynamic Assembling Simulation Software (DASS), a large set of experiments was designed to simulate the production of lots of one

thousand assemblies made of two high variation components so that the individual and combined influence of the factors involved in the production can be evaluated.

For an assembly process with a nominal target value of 30 mm, simulation results revealed, in comparison to a fully randomized assembling, an average reduction by 89% of the mean shift from a mean value equal to 29.55 mm to an improved mean equal to 29.95 mm, an average reduction by 14% of the standard deviation from 0.29 to 0.25, an average improvement of the actual capability index of the assembling process by 16% from 1.15 to 1.34, an average improvement of the potential capability index of the assembling process by 101% from 0.63 to 1.27, and an average reduction of the items out of tolerance by 100% from 28.6 per thousand opportunities to zero.

In conclusion, the proposed SFFCM-based assembling technique, a combination of the adaptive and the selective approach with emphasis in the inspection optimization, effectively helped achieve the mayor objectives of this thesis: reduce the process variation, reduce the scrap level and improve the process capability indices. In few words, it is possible to end up with low variation assemblies made of high variation components. Seen from a different perspective, a capable process ($c_p > 1.33$) was obtained by means of combining two non-capable subprocesses.

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Carlos Hernández

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ACRONYMS

ASA	Adaptive and Selective Assembling
CDNA	Cumulative de-Noised Average
CTQ	Critical To Quality
DASS	Dynamic Assembling Simulation Software
DMAIC	Definition, Measurement, Analysis, Improvement, and Control
ISO	International Organization for Standardization
LTL	Lower Tolerance Limit
MSE	Mean Square Error
MTA	Make To Assemble
MTO	Make To Order
MTS	Make To Stock
OSA	Ordered Selective Assembling
PCI	Process Capability Index
PDF	Probability Density Function
PID	Proportional Integral Derivative
QC	Quality Control
QE	Quality Engineering
QMS	Quality Management System
SAPS	Selective and Adaptive Production Systems
SDSM	Statistical Dynamic Specifications Methods
SFFCM	Statistical Feed-Forward Control Model
SPC	Statistical Process Control
SQC	Statistical Quality Control
TCS	Total Customer Satisfaction
TPM	Total Productive Maintenance
TQC	Total Quality Control
TQM	Total Quality Management
UTL	Upper Tolerance Limit
2D	Two-Dimensional
3D	Three-Dimensional

NOMENCLATURE

Statistic	Estimator	Description
c_p	$\hat{c}_p$	Potential capability index.
$c_{p,assy}$	$\hat{c}_{p,assy}$	Potential capability index of the assembly process.
$c_{p,assy,adj}$	$\hat{c}_{p,assy,adj}$	Potential capability index of the assembly process after SFFCM.
$c_{p,i}$	$\hat{c}_{p,i}$	Potential capability index of the process of Component i .
$c_{p,j,sub(j)}$	$\hat{c}_{p,j,sub(j)}$	Potential capability index of the subset j of the process of Component i .
$c_{p,i,adj,sub(j)}$	$\hat{c}_{p,i,adj,sub(j)}$	Potential capability index of the subset j of the process of Component i after SFFCM.
$c_{pk,assy}$	$\hat{c}_{pk,assy}$	Actual capability index of the assembly process.
$c_{pk,assy,adj}$	$\hat{c}_{pk,assy,adj}$	Actual capability index of the assembly process after SFFCM.
c_{pk}	$\hat{c}_{pk}$	Actual capability index.
$c_{pk,i}$	$\hat{c}_{pk,i}$	Actual capability index of the process of Component i .
$c_{pk,i,sub(j)}$	$\hat{c}_{pk,i,sub(j)}$	Actual capability index of the subset j of the process of Component i .
$c_{pk,i,adj,sub(j)}$	$\hat{c}_{pk,i,adj,sub(j)}$	Actual capability index of the subset j of the process of Component i after SFFCM.
L_{assy}	-	Nominal target of the assembly.
L_i	-	Nominal target of Component i .
$L_{i,adj,sub(j)}$	$\hat{L}_{i,adj,sub(j)}$	Adjusted target of the subset j of Component i .
μ_{assy}	$\bar{x}_{assy}$	Mean and sample mean of the assembly.
$\mu_{assy,sub(j)}$	$\bar{x}_{assy,sub(j)}$	Mean and sample mean of the subset j of the assembly.
μ_i	$\bar{x}_i$	Mean and sample mean of Component i .
$\mu_{i,sub(j)}$	$\bar{x}_{i,sub(j)}$	Mean and sample mean of the subset j of Component i .
σ_{assy}	s_{assy}	Std.Dev. and sample Std.Dev. of the assembly.
σ_i	s_i	Std.Dev. and sample Std.Dev. of Component i .

Statistic	Estimator	Description
$\sigma_{i,sub(j)}$	$s_{i,sub(j)}$	Std.Dev. and sample Std.Dev. of the subset j of Component i .
t_{assy}	-	Nominal tolerance of the assembly.
t_i	-	Nominal tolerance of Component i .
$t_{i,adj,sub(j)}$	$\hat{t}_{i,adj,sub(j)}$	Adjusted tolerance of the subset j of Component i .
$t_{i,adj,sub(j),unc}$	$\hat{t}_{i,adj,sub(j),unc}$	Adjusted tolerance of the subset j of Component i considering the measurement uncertainty.
-	$\bar{x}_{cdna}$	Cumulative de-noised average.
-	$\bar{x}_{i,cdna}$	Cumulative de-noised average of Component i
-	$\bar{x}_{i,cdna,sub(j)}$	Cumulative de-noised average of the subset j of Component i