Developing Robust Systems

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Introduction

The development of a high-speed electrophotographic printing process is a complex process requiring considerable time and investment. With the ever-increasing competitive environment, cycle times must be reduced so that new product can be aggressively introduced to meet customer needs. In addition to timely introduction, product must satisfy customer's requirements while operating within the demanding workplace environment.

Traditionally, development times for electrophotographic systems have been lengthy due to the complexity of these systems. An electrophotographic system consists of several subsystems that strongly interact with each other. The hardware and materials are complex requiring extensive subsystem development prior to full system testing and optimization. In addition, the system operating environment is very "noisy". There is little control over the "customer environment" or the paper that is used. Systems integration is difficult and time consuming.

In this paper, a process is discussed that reduces the development time for an electrophotographic system and delivers robustness performance which meets customer requirements despite the demanding operating environment. The process involves

- Development of efficient, compact stress test conditions that sufficient stress the system under development testing so that robust designs can be efficiently and rapidly developed.
- Simultaneous development of both subsystem and system technology using an interactive process.
- Highly efficient test matrices that extensively define design parameter interaction with system level "noises" so that robust designs can be efficiently identified.
- System level verification testing under stress conditions that measure performance against customer deliverable metrics.

Traditional EP Process Development

Prior to development of this process, product development was characterized by single factor at a time experimentation. Technology development relied on simple parametric models (2 or 3 factors) to drive design optimization. Testing was typically performed under nominal conditions which typically did not adequately simulate "real" customer environments. This work failed to gain a fundamental understanding of design factors that truly drove superior performance.

Development Phase

- Very long cycle times.
- Systems integration activities experienced several start/stop cycles.

PreProduction

- Prototype performance not repeatable.
- Expensive redesign and retooling was required.

Customer Introduction

- Some significant design weakness not identified until with customer.
- Erratic reliability/poor customer satisfaction.

<u>Characteristics of Development</u>

- Single factor at a time experimentation.
- Reliance on simple (2 -3 factor) parameter models to drive design optimization.
- Extensive testing under nominal conditions at nominal design setpoints.
- Reactive engineering - Design, Test, Fix
- Failed to gain fundamental understanding of factors that are truly significant to performance (too few/too many carried through product cycle)

This process allowed inadequate designs to be introduced into a product design. This led to a reactive engineering environment during the final stages of product development and early manufacture. Full systems testing would identify problems or weaknesses in the design. The problems would be fixed with a subsystems focus, which general lead to a solution that created additional problems in other areas of the system. This iterative build, text, fix cycle slowed progress and contributed significantly to late product introductions. Development costs were increased since redesign and retooling was necessary.

Once introduced, design weaknesses were identified that had not been seen during product development. The customer environment stressed the product design outside the window evaluated in product development. Performance was not reliable and customer satisfaction was low.

New EP Development Process

A superior development process was needed. Shorter development times were needed and the R&D to manufacturing process had to be more predictable and repeatable.

Key to this process was understanding the important “customer” noises that the product would be subjected to in the marketplace. Simulating these noises during product development was absolutely required to access the system design performance and maturity under realistic conditions.

Understanding these noises was only the beginning. Testing procedures and processes were needed to identify key design parameters and the proper design levels so that the system sensitivity to stress “noise” conditions was minimized. This process would have to encompass both subsystem and system level performance and generate a system design that met program goals and objectives.

Such a process was developed that met the objectives outlined above. This process included the following steps.

1. Noise (Stress) Testing
- Develop efficient stress matrix.
- Benchmark baseline performance.

2. Parameter Design Testing
- Simultaneous testing of several significant design variables.
- Identify most robust combination of design settings.

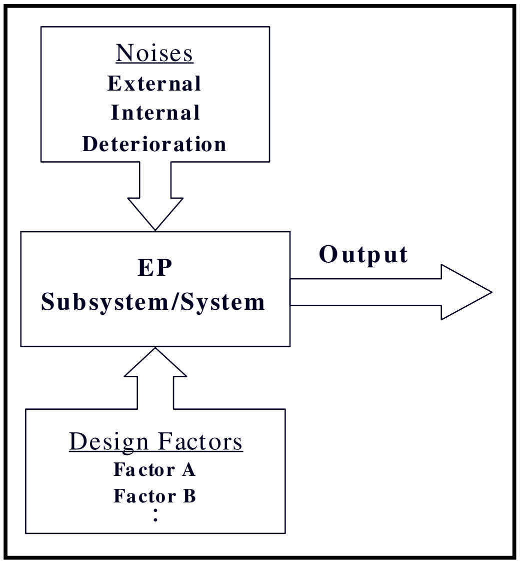
3. System Verification Testing
4. Iterative Testing Cycle

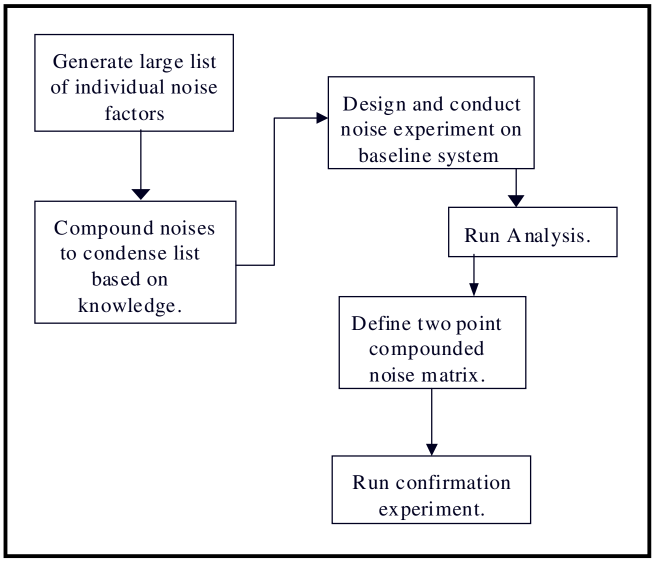
These specific tests will be discussed in detail in the following sections.

Noise Testing

The objective of noise testing is to identify a compounded noise matrix that can be used to sufficiently stress a subsystem or system design during development testing.

A compounded noise matrix reduces the number of test conditions that must be run. Conditions are selected that tend to push the quality characteristics of the system under test in opposite directions. As an example, if solid area density was a characteristic that was required, noises would be selected that pushed the solid area density high and lower. If selected properly, testing under these noise conditions result in variation that is considerably larger than variation due to random run to run noises. Tests can therefore be kept relative short and results are very repeatable.





The process of identifying a noise test matrix involves the following steps:

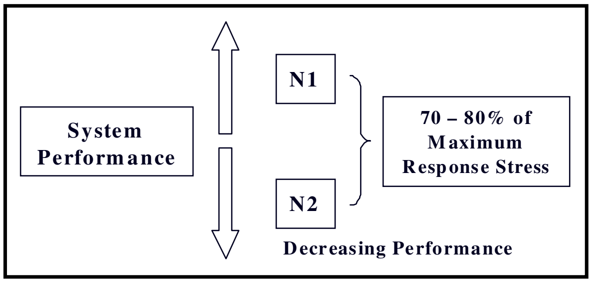
1. **Identification of Noise Factors: A** list of noise factors that are considered to impact the quality characteristic(s) of interest is generated. A small group of knowledgeable people is best for this exercise. Factors are identified as noises if they cannot be controlled in the customer environment. Examples are temperature, paper type, humidity, etc. Typically 30 or more factors can be easily identified for systems. Subsystems may have fewer.

2. **Compounding and Prioritizing Noise Factors:** Once this noise list has been generated, noises are compounded based on experience and knowledge of the process. Compounding is done when the interrelationship between two or more noise factors is known. Consider the noise factors for paper movement in a machine. With a friction feed system it may be more difficult to move a heavy sheet compared to a light sheet of paper. It is also know that a smoother sheet of paper presents less friction force between the feeder wheel and the paper surface. Compounding these factors would involve two test papers; one being heavy and smooth and the other light and rough. The heavy, smooth paper might promote misfeeds whereas the light, rough paper would promote multifeeds.

3. **Selection of Noise Factors to Test:** Once the list is compounded as best as possible, the top 11 factors (or compounded factors) are chosen. Many times this involves engineering judgement. An efficient and effective way of doing is this is by pareto voting within a small group.

4. **Noise Factor Experiment:** These 11 noise factors are then evaluated by designing an experiment using the L-12 Orthogonal array. The test is done on the initial baseline design and benchmarks the performance of the starting design. Two levels are chosen for each noise factors. Twelve experiments are conducted, each having a unique combination of the noise factor levels.

5. **Establish Two Point Compounded Noise Matrix:** From an analysis of the means, specific compounded noise combinations can be chosen. Analysis of variance can be conducted to eliminate less significant noises. Typical results show that roughly half the noise factors can be eliminated. By compounding the most significant noises, 70 – 80% of the maximum stress response can be obtained.



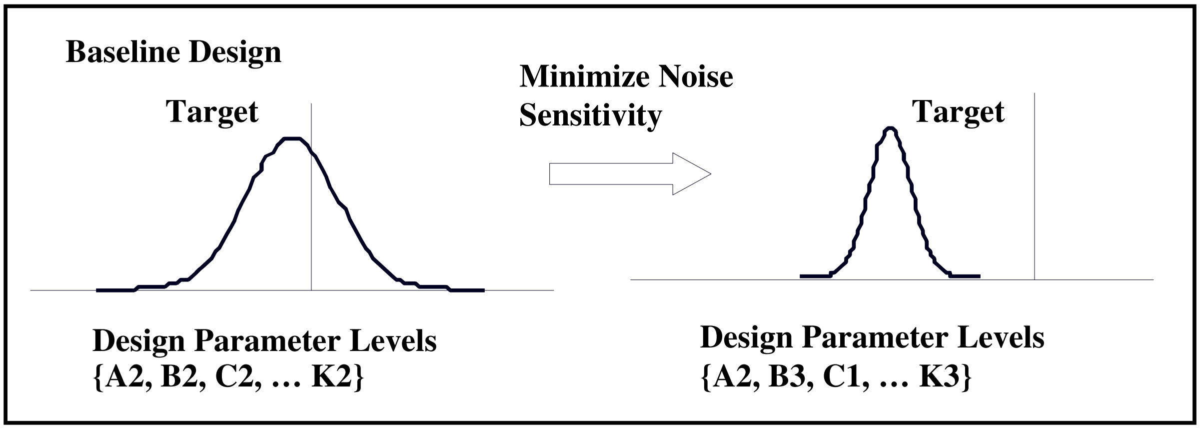
The development of a compound noise stress matrix has additional benefits. Testing is conducted with the baseline design, so that an adequate benchmark for robustness development is established. Noise testing provides a test vehicle for perfecting the testing procedure that will be used in identifying robust design parameter levels and determines the magnitude of uncontrolled noises.

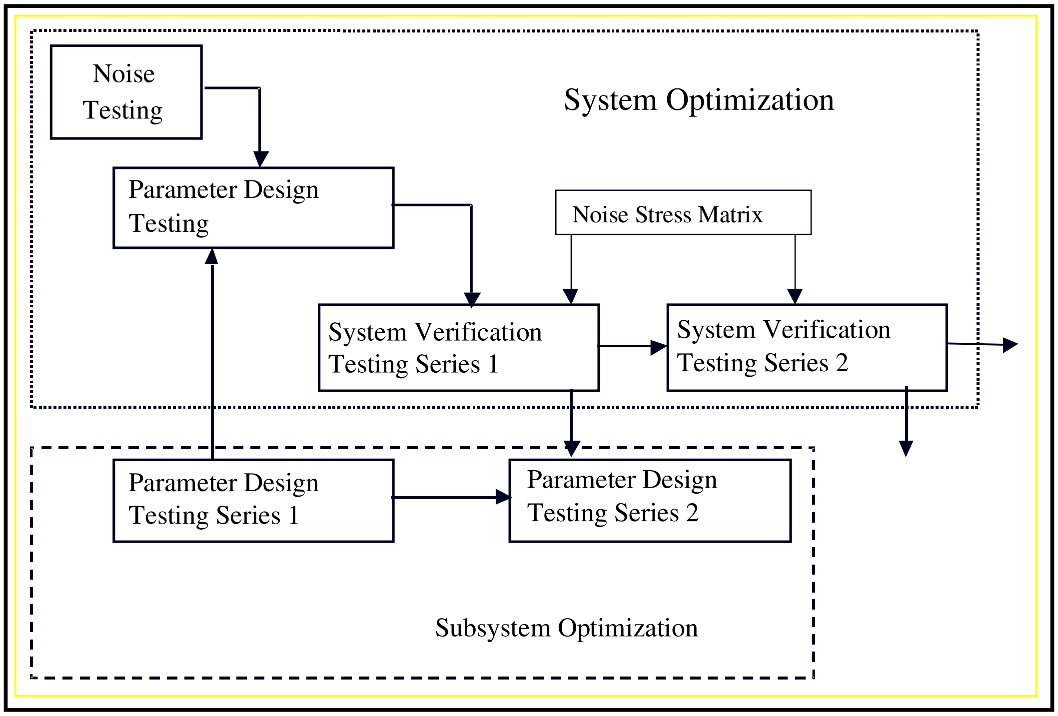
Parameter Design Testing

Following the development of a noise stress matrix, parameter design testing is done. The objective of this experimentation is to identify design factor levels that minimize the system output sensitivity to noise. Several factors are studied simultaneously (6 –7 minimum) instead of a single factor at a time experiment. The experiments are designed so that each design factor’s interaction with noise is completely studied. This is done using supersaturated orthogonal arrays that do not permit factor to factor interactions to be studied. Experience has shown that it is far more important to study as many design factors as possible. By using an understanding of the physics of the technology and carefully selected system responses, the design space can be efficiently explored to identify the most robust combination of design factor levels.

To make the analysis of the experimental data meaningful, a robustness metric is needed. The S/N ratio is commonly used. The S/N ratio is simply the ratio of the “energy of the signal” to the “energy of the noise”. For every design combination tested during parameter design testing, performance is evaluated across the noise matrix. The data will exhibit variability. The S/N ratio gives a measure of the strength of the intended response compared with the variability associated with the response to the noise. For higher levels of robustness, the S/N metric must be maximized.

Robustness is a two step optimization process. Parameter design is intended to determine two things. The first is to find the combination of design factors that provide the highest level of robustness. Typically this leads to a system response that is robust but not on target. A “tuning” design factor must be identified. This factor is used to adjust the robust system to target performance without sacrificing robust performance. Using a two step optimization approach allows this to be done.





System Verification Testing

Once parameter design testing has been conducted, full system verification testing is run. The purpose of the verification testing is to confirm that robust performance across customer simulated noises has been obtained. Testing includes both short term and long term evaluations. Verification testing involves no testing under nominal operation conditions. This does not provide useful information and is not an efficient use of experimental resources and energy. The design configuration that is tested is the most robust design identified during parameter design testing and development. The testing is conducted continuously and data is collected at predetermined points. Poor results are recorded, but changes to the system design are not made and “modifications” to the design in response to poor results are not made. The purpose is to accurately quantify system performance under a set design.

Iterative Testing Cycle

This testing strategy is conducted simultaneously on both the subsystem and system level. The starting point is typically the subsystem or system design that was used for initial feasibility testing and demonstration. Subsystem testing typically leads system testing development by one design iteration so that initial robustness on a subsystem level can be partially established. This subsystem work becomes input for the design of parameter design testing on the system level. Once one design iteration on both a subsystem and system level has been completed, system verification testing is started. Based on system verification testing results, further improvements to robustness are developed for each of the subsystems. The results from this second design iteration are input into the second systems verification testing cycle. Using this iterative approach, incremental improvements are easily measurable. Once program requirements are met, the design is released for commercialization.

Conclusions

Experience with this development approach has shown superior results compared with the traditional approach that had once been associated with EP systems development. It has been found that robust design, using an iterative testing approach has yielded the following benefits.

- Development process is proactive.
  - Sensitivity to noise factors is minimized up front.
  - Build, test, fix cycle is minimized.
- Development process is accelerated.
  - Compact stress test matrix is very efficient. Tests are shorter.
  - Testing is more robust. Results are much more repeatable.

- Superior downstream repeatability. Production designs emulated prototype performance.

- Costs are decreased. Rework is minimized.

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Biography

Dr. Jeffery C. Blood is Vice President of R & D at Heidelberg Digital L.L.C. in Rochester, NY. He has been involved with imaging at Heidelberg and previously at Kodak for 19 years, working in the fields of electrophotography, solid state electronics, ink jet, and photography. He received his Ph.D. in Organic Chemistry from the University of Wisconsin at Madison in 1981.