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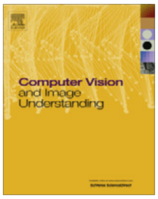

Sensitivity analysis for biometric systems: A methodology based on orthogonal experiment designs[☆]

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ABSTRACT

The purpose of this paper is to introduce an effective and structured methodology for carrying out a biometric system sensitivity analysis. The goal of sensitivity analysis is to provide the researcher/developer with insight and understanding of the key factors—algorithmic, subject-based, procedural, image quality, environmental, among others—that affect the matching performance of the biometric system under study. This proposed methodology consists of two steps: (1) the design and execution of orthogonal fractional factorial experiment designs which allow the scientist to *efficiently* investigate the effect of a large number of factors—and interactions—simultaneously, and (2) the use of a select set of statistical data analysis graphical procedures which are fine-tuned to unambiguously highlight important factors, important interactions, and locally-optimal settings. We illustrate this methodology by application to a study of VASIR (Video-based Automated System for Iris Recognition)—NIST iris-based biometric system. In particular, we investigated $k = 8$ algorithmic factors from the VASIR system by constructing a $(2^{6-1} \times 3^1 \times 4^1)$ orthogonal fractional factorial design, generating the corresponding performance data, and applying an appropriate set of analysis graphics to determine the relative importance of the eight factors, the relative importance of the 28 two-term interactions, and the local best settings of the eight algorithms. The results showed that VASIR's performance was primarily driven by six factors out of the eight, along with four two-term interactions. A virtue of our two-step methodology is that it is systematic and general, and hence may be applied with equal rigor and effectiveness to other biometric systems, such as fingerprints, face, voice, and DNA.

1. Introduction

Biometrics is the automated recognition of individuals based on their biological and behavioral characteristics [1]. The characteristics can include fingerprints, face, iris, ocular area, retina, ear, voice, DNA, signature, gait, and hand geometry among others. The use of biometrics has many advantages—especially as an alternative to keys, passwords, smartcards, and other artifacts for physical entry. In this regard, biometric-based technologies are increasingly being incorporated into specific security fields and applications, such as industrial access control, law-enforcement, military, border control, and forensics [2].

A significant problem in biometric studies is that researchers/developers often present results that lack an assessment of intrinsic system uncertainty. A high degree of input and output numerical precision often gives the impression of great accuracy, but neglects to give attention to the critical questions of the sensitivity of the final results to different algorithms, environments, subject characteristics, and biometric sample conditions [3]. Hornberger and Spear [4] made the following paraphrased statement about simulation models: Most such models are complex, with many parameters, state-variables and underlying non-linear relations; under optimal circumstances, such systems have many degrees of freedom and—with judicious adjustments—are susceptible to over-fitting with both plausible structure and "reasonable" parameter values. We believe that the above statement applies equally well for biometric systems, especially for iris recognition system.

Sensitivity analysis has been successfully conducted in areas such as computer vision and computer network [5–7]. Sensitivity analysis is the study of how the output of a system is affected by different inputs to the system [8]. In essence, a biometric system is a data monitoring and decision-making "machine." A good biometric system has a high proportion of correct decisions. All biometric systems are susceptible to incorrect decisions—especially in the presence of less-than-optimal conditions.

In practice, the performance of many biometric systems is frequently examined and optimized via a series of one-factor-at-a-time experiment designs in which most factors in the system are

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held constant while one factor is focused on and varied to examine its effect. This design, though popular [9,10] has the disadvantage that it can yield grossly biased (incorrect) estimates of factor effects. Further, this design has no capacity to estimate factor interactions—which are intrinsic to many biometric systems.

The motivation for this paper is thus to introduce to the biometrics community an alternative method for conducting a sensitivity analysis with the advantage that:

(1) The system will be better understood.
(2) The system will be better characterized.
(3) The system will be better optimized—with the net effect that system performance is significantly improved in a computationally efficient fashion.

Thus, in short, the objective of this paper is to introduce and apply a structured "Sensitivity Analysis" approach for gaining insight and understanding about the system's key components—those which most affect the quality and performance of a biometric system—and to optimize the settings of these key components.

Sensitivity analysis as we describe it has two separate and distinct steps:

(1) *Experiment Design* (the structured plan for collecting the data), and
(2) *Statistical Analysis* (the structured methodology for analyzing the data).

Both parts are critical, and when optimally used in concert yield enhanced insight into the relative importance and effect of the various computational components (and interactions) affecting biometric system performance. The experiment design and data analysis are demonstrated by a particular iris-based biometric system, VASIR (Video-based Automated System for Iris Recognition), which has verification capability for both traditional still iris images and video sequences captured at a distance while a person walks through a portal [11].

The general structure of this paper is threefold:

(1) *Orthogonal fractional factorial design:* Introduce to the biometrics community a structured orthogonal fractional factorial experiment design methodology to efficiently gain insight and understanding ("sensitivity analysis") of critical system parameters, interactions, and their optimal settings—this introduces and applies an established method within the statistical community [12,13].
(2) *Statistical analysis:* Present effective and insightful statistical analysis methodologies for carrying out sensitivity studies.
(3) *Demonstration with VASIR:* Demonstrate our experiment design and analysis methodologies for VASIR, with potential application to the broader biometrics field.

This sensitivity analysis approach provides a tool for understanding the computational components affecting the overall performance of a biometric system. Based on such understanding, the logical follow-up is to carry out an optimization analysis (identifying the optimal global settings of the components), and a robustness analysis (assessing the range of validity for our sensitivity and optimization conclusions). Our current paper focuses on the details of the sensitivity analysis only. To demonstrate the elements of the sensitivity analysis approach, we restrict our focus to a fixed setting for two robustness factors: (1) eye position (left eye only), and (2) image type (video matching: non-ideal to non-ideal image only).

2. Sensitivity analysis methodology

Sensitivity analysis is the experimental process by which we determine the relative importance of the various factors of a system. Suppose a system has k factors (input parameters) which potentially affect its performance. The minimal deliverable of a sensitivity analysis is to produce a ranked list of those k factors—ordered most to least important. For complicated systems (e.g., biometrics), a more desirable deliverable is to produce a ranked list which contains not only the k main factors, but also includes the various interactions of a system. To generate such a list implicitly means that each factor effect must be estimative, and such estimates should have as minimal bias and uncertainty.

As it turns out, such bias and uncertainty is driven primarily by the choice of experiment design that the analyst employs—some designs yield noisy effect estimates, while others yield very accurate estimates.

A good experiment design is important—it assures that the resulting data from the design has the capacity to answer the scientific question at hand—in particular, the data must have the capacity to yield a valid and rigorous ranking of the factors under study. Important as the experiment design component is, a complementary component is also important, namely, the statistical analysis methodology employed to analyze the data resulting from the design—what techniques must be brought to bear on the data so as to optimally estimate, order, and highlight the various factor effects. Hence sensitivity analysis consists of two separate and distinct steps:

(1) *Experiment Design* (the structured plan for collecting the data), and
(2) *Statistical Analysis* (the structured methodology for analyzing the data).

The detailed elements of the two components for our sensitivity analysis are illustrated by application to a particular iris-based biometric system: VASIR (Video-based Automated System for Iris Recognition), which has verification capabilities not only for traditional still iris images but also for video sequences taken at a distance with moving subject (see the details in Section 3).

2.1. Experiment design

Experiment design as a discipline is a systematic and rigorous approach for scientific and engineering problem-solving. The general goal of experiment design is threefold:

(1) To produce insight and understanding into the factorial dependencies of a system.
(2) To produce unambiguous, valid, and defensible conclusions.
(3) To achieve both of the above with as small a sample size (time and cost) as possible [14].

Sensitivity Analysis offers to the biometric scientist the understanding and insight as to what is important and what is not in a system—and where the scientist should focus near-term and long-term research efforts. In this regard we shall briefly review and compare four commonly used experiment designs for sensitivity analysis: (1) Randomization Designs (Monte Carlo), (2) One-Factor-at-a-time (1FAT) Designs, (3) Full Factorial Designs, and (4) Orthogonal Fractional Factorial Designs.

(1) *Randomization Designs (Monte Carlo).*

Monte Carlo is a common methodology for many scientific sensitivity analysis studies. In essence, it considers the entire population space of factors and settings and then randomly samples a