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14. ABSTRACT

For reliability-based design optimization (RBDO), sensitivity analysis capability is a major bottleneck for broader use of RBDO methods in multidisciplinary M&S applications of Army complex physical systems. To overcome this bottleneck, a sequential sampling-based dynamic Kriging (DKG) method is developed. The DKG method has been integrated with the Iowa-RBDO software system that is developed under US Army TARDEC sponsorship. For large-scale simulation models, the total number of simulations carried out for surrogate modeling could be limited due to computation resource. In such cases the inaccuracy and uncertainty of the surrogate model needs to

15. SUBJECT TERMS

Reliability-Based Design Optimization, Input Uncertainty, Model Uncertainty

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Report Title

SYSTEM RELIABILITY-BASED DESIGN OPTIMIZATION UNDER INPUT AND MODEL UNCERTAINTIES

ABSTRACT

For reliability-based design optimization (RBDO), sensitivity analysis capability is a major bottleneck for broader use of RBDO methods in multidisciplinary M&S applications of Army complex physical systems. To overcome this bottleneck, a sequential sampling-based dynamic Kriging (DKG) method is developed. The DKG method has been integrated with the Iowa-RBDO software system that is developed under US Army TARDEC sponsorship. For large-scale simulation models, the total number of simulations carried out for surrogate modeling could be limited due to computation resource. In such cases the inaccuracy and uncertainty of the surrogate model needs to be quantified. For this, the weighted Kriging variance method is developed using the corrected Akaike information criterion (AICc) to generate a confidence interval of the surrogate model; and the upper bound of the confidence interval is used to obtain confidence-based RBDO optimum design that satisfies the target reliability. In practical industrial application, often input data are not sufficient enough to generate true input distribution models for reliability analysis and RBDO. When only the limited input data are provided, uncertainty is induced on the input probability model and this uncertainty propagates to the reliability output which is defined as the probability of failure. Thus, the reliability output is considered to have a probability distribution in this research, which is obtained as a combination of consecutive conditional probabilities of input distribution type and parameters using Bayesian approach. Using the probability of the reliability output as constraint, a confidence-based RBDO (C-RBDO) problem is formulated. For effective C-RBDO process, the design sensitivity of the new probabilistic constraint is derived. As an alternative for DKG, a virtual support vector machine (VSVM) is developed to improve the efficiency of the sampling-based RBDO. The VSVM is successfully developed and applied to the sampling-based RBDO and demonstrated to be faster for MCS in evaluation of the probability of failure and its design sensitivity compared to the very accurate DKG method that the research team has developed in this project. Finally four strategies are developed to improve the dynamic Kriging (DKG) method: (1) accurate correlation parameter estimation, (2) penalized maximum likelihood estimation (PMLE), (3) correlation model selection, and (4) mean structure selection.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u>   <u>Paper</u>

TOTAL:

Number of Papers published in peer-reviewed journals:

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<u>Received</u>   <u>Paper</u>

TOTAL:

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Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received   Paper

02/01/2014 31.00 Hyeongjin Song, K.K. Choi, Ikjin Lee, Liang Zhao, David Lamb. Sampling-based RBDO using Probabilistic Sensitivity Analysis and Virtual Support Vector Machine,
ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. 13-AUG-12, . : ,

02/01/2014 32.00 Hyunkyoo Cho, K.K. Choi, Ikjin Lee, David Gorsich. Confidence Level Estimation and Design Sensitivity Analysisfor Confidence-based RBDO,
ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. 13-AUG-12, . : ,

08/08/2011 22.00 K.K. Choi, Yoojeong Noh, Ikjin Lee. Reliability-Based Design Optimization with Confidence Level for Problems with CorrelatedInput Distributions,
6th China-Japan-Korea Joint Symposium on Optimization of Structural and Mechanical Systems. 22-JUN-10, . : ,

08/08/2011 23.00 Kyung K. Choi, Yoojeong Noh, Liang Zhao, Ikjin Lee, David Gorsich. Sampling-Based Stochastic Sensitivity Analysis Using Score Functions for RBDO Problems with Correlated Random Variables,
ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. 15-AUG-10, . : ,

08/08/2011 24.00 Yoojeong Noh, Kyung K. Choi, Ikjin Lee, David Gorsich. Reliability-based Design Optimization with Confidence Level for Non-Gaussian Distributions Using Bootstrap Method,
ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. 15-AUG-10, . : ,

08/08/2011 25.00 Liang Zhao, K.K. Choi, Ikjin Lee. A Metamodeling Method Using Dynamic Kriging and Sequential Sampling,
3th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. 13-SEP-10, . : ,

08/08/2011 26.00 Ikjin Lee, K.K. Choi, Liang Zhao. Sampling-Based RBDO Using the Dynamic Kriging (D-Kriging) Method and Stochastic Sensitivity Analysis,
AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference. 13-SEP-10, . : ,

08/08/2011 27.00 Liang Zhao, K.K. Choi, Ikjin Lee, David Lamb, David Gorsich. Conservative Surrogate Model using Weighted Kriging Variance for Sampling-based RBDO,
9th World Congress on Structural and Multidisciplinary Optimization. 13-JUN-11, . : ,

08/08/2011 30.00 Hyeongjin Song, K.K. Choi, Ikjin Lee, Liang Zhao, David Lamb. Adaptive Virtual Support Vector Machine for the Reliability Analysis of High-Dimensional Problems,
ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. 23-AUG-11, . : ,

08/08/2011 28.00 K.K. Choi, Ikjin Lee, Liang Zhao, Yoojeong Noh, David Lamb, David Gorsich. Sampling-Based RBDO Using Stochastic Sensitivity and Dynamic Kriging for Broader Army Applications,
2011 NDIA GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM. 09-AUG-11, . : ,

08/08/2011 29.00 Ikjin Lee, Kyung K. Choi, David Gorsich. Equivalent Standard Deviation to Convert High-reliability Model to Low-reliability Model for Efficiency of Sampling-based RBDO,
ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference. 28-AUG-11, . : ,

TOTAL: 11

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received   Paper

02/01/2014 33.00 Liang Zhao, K. K. Choi, Ikjin Lee. Metamodeling Method Using Dynamic Kriging for Design Optimization, AIAA Journal (10 2010)

02/01/2014 38.00 Hyeongjin Song, K.K. Choi, Ikjin Lee, Liang Zhao, David Lamb. Adaptive Virtual Support Vector Machine for Reliability Analysis of High-Dimensional Problems, Structural and Multidisciplinary Optimization (12 2011)

02/01/2014 37.00 Liang Zhao, K.K. Choi, Ikjin Lee, David Gorsich. Conservative Surrogate Model using Weighted Kriging Variance for Sampling-based RBDO, ASME Journal of Mecahnical Design (12 2011)

02/01/2014 36.00 Ikjin Lee, K. K. Choi, Yoojeong Noh, David Lamb. Comparison Study between Probabilistic and Possibilistic Methods for Problems under a Lack of Correlated Input Statistical Information, Structural and Multidisciplinary Optimization (07 2102)

02/01/2014 35.00 Yoojeong Noh, K. K. Choi, Ikjin Lee, David Gorsich, David Lamb. Reliability-based Design Optimization with Confidence Level for Non-Gaussian Distributions Using Bootstrap Method, ASME Journal of Mecahnical Design (02 2011)

02/01/2014 34.00 Ikjin Lee, K.K. Choi, Liang Zhao. Sampling-Based RBDO Using the Stochastic Sensitivity Analysis and Dynamic Kriging Method, Structural and Multidisciplinary Optimization (10 2010)

02/07/2011 2.00 I. Lee, K. Choi, Y. Noh, L. Zhao, D. Gorsich. Sampling-Based Stochastic Sensitivity Analysis Using Score Functions for RBDO ProblemsWith Correlated Random Variables, (02 2011)

02/07/2011 13.00 K. Choi. SYSTEM RELIABILITY-BASED DESIGN OPTIMIZATION UNDER INPUT AND MODEL UNCERTAINTIES, (05 2009)

02/07/2011 12.00 K. Choi. System RBDO Under Input and Model Uncertainties, (02 2011)

02/07/2011 11.00 Y. Noh, K. Choi, I. Lee, D. Gorich, D. Lamb. Reliability-based design optimization with confidence level under input model uncertainty due to limited test data, (01 2011)

02/07/2011 10.00 K. Choi, Y. Noh, I. Lee. Reliability-Based Design Optimization with Confidence Level for Problems with Correlated Input Distributions, (06 2010)

02/07/2011 9.00 Y. Noh, K. Choi, I. Lee. Reliability-based Design Optimization with Confidence Level for Non-Gaussian Distributions Using Bootstrap Method, (08 2010)

02/07/2011 8.00 I. Lee, K. Choi, Y. Noh, L. Zhao. Sampling-Based Stochastic Sensitivity Analysis Using Score Functions for RBDO Problems with Correlated Random Variables, (08 2010)

02/07/2011 7.00 I. Lee, K. Choi, L. Zhao. Sampling-Based RBDO Using the Dynamic Kriging
(D-Kriging) Method and Stochastic Sensitivity Analysis
,
(02 2011)

02/07/2011 6.00 L. Zhao, K. Choi, I. Lee. A Metamodeling Method Using Dynamic Kriging and Sequential Sampling
,
(02 2011)

02/07/2011 1.00 L. Zhao, K. Choi, I. Lee. A Metamodeling Method Using Dynamic Kriging and
Sequential Sampling
,
(02 2011)

02/07/2011 3.00 I. Lee, K. Choi, D. Gorsich. System reliability-based design optimization using the MPP-based dimension
reduction method,
(12 2009)

02/07/2011 4.00 Y. Noh, K. Choi, I. Lee. Comparison study between MCMC-based and weight-based Bayesian methods
for identification of joint distribution,
(07 2010)

02/13/2011 5.00 Y. Noh, K. Choi, I. Lee, D. Gorsich, D. Lamb. Reliability-based Design Optimization with Confidence Level
for Non-Gaussian Distributions Using Bootstrap Method,
ASME Journal of Mecahnical Design (02 2011)

08/08/2011 15.00 Ikjin Lee , K. K. Choi, David Gorsich. System reliability-based design optimizationusing the MPP-based
dimension reduction method,
Structural and Multidisciplinary Optimization (12 2009)

08/08/2011 16.00 Yoojeong Noh, K. K. Choi, Ikjin Lee. Comparison study between MCMC-based and weight-based
Bayesian methods for identification of joint distribution,
Structural and Multidisciplinary Optimization (07 2010)

08/08/2011 17.00 Ikjin Lee, K.K. Choi, Yoojeong Noh, Liang Zhao, David Gorsich. Sampling-Based Stochastic Sensitivity
Analysis Using Score Functions for RBDO Problems With Correlated Random Variables,
Journal of Mechanical Design (02 2011)

08/08/2011 18.00 Yoojeong Noh, K.K. Choi, Ikjin Lee, David Gorsich, David Lamb. Reliability-based design optimization with
confidence levelunder input model uncertainty due to limited test data,
Structural and Multidisciplinary Optimization (01 2011)

08/08/2011 19.00 K.K. Choi, Liang Zhao, Ikjin Lee. Metamodeling Method Using Dynamic Kriging for Design Optimization,
AIAA Journal (08 2011)

08/08/2011 20.00 Ikjin Lee, K.K. Choi, Liang Zhao. Sampling-Based RBDO Using the Stochastic Sensitivity Analysis and
Dynamic Kriging Method,
Structural and Multidisciplinary Optimization (04 2011)

08/08/2011 21.00 Yoojeong Noh, Kyung K. Choi, Ikjin Lee, David Gorsich, David Lamb. Reliability-based Design
Optimization with Confidence Level for Non-Gaussian Distributions Using Bootstrap Method,
Journal of Mechanical Design (07 2011)

TOTAL: 26

Number of Manuscripts:

Books

<u>Received</u>   <u>Paper</u>

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Kyung K. Choi	0.08	
FTE Equivalent:	**0.08**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME
Liang Zhao
Hyeiongjin Song
Total Number: 2

Names of other research staff

NAME   PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

Inventions (DD882)

SCIENTIFIC ACCOMPLISHMENTS

Objective: Develop new technology and numerical methods for system-level reliability-based design optimization (RBDO) in order to increase the associated target confidence level under input and simulation model uncertainties.

Approach: Four technical developments are pursued:

1. For improved product reliability, design guidelines and/or standards have been recently modified to incorporate input uncertainty significantly in the modeling and simulation (M&S) based design process. However, since the reliability-based design optimization (RBDO) method requires sensitivities of performances with respect to design and other random input variables, sensitivity analysis capability becomes a major bottleneck for broader use of RBDO methods in various M&S applications of Army complex physical systems. To overcome this bottleneck, during the 1st year of the project, the sequential sampling-based dynamic Kriging (DKG) method is developed to generate the most accurate surrogate model in an efficient manner compared with five other popular surrogate modeling methods. To make the DKG method effective and efficient for large scale complex applications, four parallelization strategies have been implemented using the parallel computing tool box in Matlab. The DKG method has been integrated with the Iowa RBDO (I-RBDO) software that is developed under TARDEC sponsorship. For successful application of the sampling-based RBDO method to the development of reliable products with desirable performance, we will develop a prediction method for confidence levels of the simulation models and thus be able to certify the simulation-based RBDO result with the target confidence level.

2. During 2nd year of the project, three developments are made. First, to verify the accuracy of the Dynamic Kriging (DKG) method, a comprehensive comparison study has been carried out with four other popular surrogate modeling methods. In this comparison study, the DKG method is demonstrated to be the accurate method. Moreover, the sequential sampling in SS-DKG improved the accuracy of the obtained surrogate models further. Second, for practical engineering applications with large-scale simulations, the total number of simulations carried out for surrogate modeling is limited due to computation resource. In such cases the inaccuracy and uncertainty of the surrogate model needs to be quantified. For this, the weighted Kriging variance method is developed using the corrected Akaike information criterion (AICc) to generate a confidence interval of the surrogate model and use the upper bound of the confidence interval to have certain confidence that the RBDO optimum design satisfies the target reliability. Third, for such large-scale complex applications, the total computational time for SS-DKG and sampling-based RBDO could be large to be unaffordable if the number of constraints is large. In the platform developed in the TARDEC project, the parallel computing toolbox in Matlab is used to deploy the parallel computing strategy.

3. In the 3rd year, the project was focused on (1) the input model uncertainty and its propagation to reliability analysis output (probability of failure); and (2) virtual support vector machine (VSVM) and efficiency strategies for sampling-based reliability-based design optimization (RBDO). For the 1st research topic, often input data are not sufficient enough for practical industrial problems to generate true input distribution models for reliability analysis and RBDO. Consequently, inaccurate input distribution models will lead to deficiency in design engineer's confidence in the obtained RBDO designs. Therefore, a confidence concept needs to be developed for the output. For that purpose, characterization of distribution of the output, not an output value, is assessed in our research during the third year. To do this, dependency of the probability of output is decomposed into the probability of input distribution parameters and input distribution types. Bayesian approach is used for the decomposition, and the correlation of input variables are estimated using copulas. For practical applications, Monte Carlo simulation (MCS) is used. Once the confidence measure is established, a new confidence-based RBDO problem is formulated. In the confidence-based RBDO problem, not only the target output value, but also target confidence level can be set by user. Thus, the optimum design of the confidence-based RBDO will satisfy the target output with target confidence level; and the user can obtain a reliable optimum design even when input data are not sufficient enough to generate true input distribution models. For the confidence-based RBDO problem, the design sensitivity analysis method for the confidence measure needs to be developed. For the 2nd research topic, VSVM is developed to improve the efficiency of the sampling-based RBDO. The VSVM is successfully developed and applied to the sampling-based RBDO and demonstrated to be faster for MCS in evaluation of the probability of failure and its design sensitivity compared to the very accurate dynamic Kriging (DKG) method that the research team has developed in this project. Transformations/Gibbs sampling method is also introduced for uniform samples in the hyper-spherical local window. A group sampling method has been developed, which can replace the previous sequential sampling method developed by the research team for parallel computing...

4. In the 4th year, the project was focused on (1) reliability-based design optimization (RBDO) with confidence level of output (probability of failure); and (2) accuracy improvement strategies for the Kriging method by using correlation model and mean structure selections. For the 1st research topic, it is assumed that given input data is not sufficient enough to generate a true input probabilistic distribution for reliability analysis and RBDO. Under the assumption, uncertainty on the input model will lead a designer to consider confidence level of the RBDO optimum. To secure a certain level of confidence level of output at the optimum, confidence-based RBDO (C-RBDO), which utilizes a distribution of output, not an output value, has been developed. C-RBDO does not require an input distribution, whereas it requires only input data. When the input data is given, C-RBDO calculates probabilities of input parameters and candidate distribution types using Bayesian approach. According to calculated probabilities, Montel Carlo samples are generated and the output is calculated at the each sample. By doing this, the distribution of output is obtained and confidence level of output can be acquired from the distribution. Hence, a user can obtain

an optimum which satisfies target output with target confidence level using C-RBDO. Furthermore, design sensitivity of C-RBDO is developed as well to achieve the optimum accurately and efficiently. Therefore a user is able to obtain a reliable optimum design effectively even when insufficient amount of data is provided. In this year, the accuracy and efficiency of C-RBDO has been significantly improved and C-RBDO is tested with a two-dimensional mathematical example. For the 2nd research topic, four strategies are introduced to improve the dynamic Kriging (DKG) method. They are (1) accurate correlation parameter estimation, (2) penalized maximum likelihood estimation (PMLE), (3) correlation model selection, and (4) mean structure selection. These four accuracy improvement strategies are combined into one scheme to improve the accuracy of the Kriging method and finally to reduce the number of samples in RBDO.

Scientific barriers: Input variables which are correlated with joint non-Gaussian CDFs. Correlations between input variables, or performances which are nonlinear functions of multi-variables, which makes first-order reliability method performance unacceptable.

Significance: Extend optimum design to a variety of input uncertainties in material properties, geometrical dimensions, and operational conditions, as well as statistical uncertainties due to limited test data and lack of information.

Accomplishments:
1. Developed a new dynamic Kriging (DKG) method (probabilities of input parameters and candidate distribution types calculated by Bayesian methods) to produce an accurate surrogate model (year 1), shown to be more accurate than existing surrogate methods (year 2), and implemented on parallel HPC.
2. Constructed a conservative surrogate model using the weighted Kriging variance where the weight is determined by the relative change in the corrected Akaike Information Criterion (AICc) of DKG.
3. Established the propagation of input model uncertainty to the reliability analysis output (probability of failure). Identified the probabilities of the distribution parameters and types using Bayesian approach and acquired the distribution of output using MCS. Analytically derived the design sensitivity of confidence-based RBDO (year 3).
4. Further improved the accuracy and efficiency of confidence-based RBDO (C-RBDO) by replacing a finite difference approximation within the analytic model by an analytic expression, making the design sensitivity of confidence level of output now fully analytic. (4th year)
5. The correlation parameter between the input variables (as random variables) was previously calculated from input data; it is now represented as a probability distribution.
6. Computational complexity of C-RBDO is greater than RBDO due to use of confidence intervals rather than point estimates for constraints; this is made less inefficient through several computational strategies (such as replacing some C-RBDO iterations by DDO and conventional RBDO iterations, using the sensitivity of these conventional iterations as a more useful initial gradient for descent, using reusable MC simulation to replace NxM samples by N samples that are mapped to M outputs).
7. Developed VSVM (virtual support vector machine) to improve efficiency by 14-30 times over DKG in MCS for reliability analysis at similar accuracy.
8. Improved the accuracy of DKG by applying a genetic algorithm to generalized pattern search for MLE in order to decrease dependence on initial design, by introducing penalized MLE to improve performance in small DoE sample sizes, and by selecting mean structure based on cross-validation error rather than by process variance.

Collaborations and leveraged funding: Scientific liaison and co-publications (8 archived journal papers and 10 conference papers) with TARDEC.

Conclusions: Accomplishments of the ARO research provide new computational method for accurately modeling distributions of the correlated input variables using copula; confidence of the reliability of RBDO results when only limited data is available for the input modeling; confidence of the reliability of RBDO results by constructing conservative Kriging-based surrogate model; providing an alternative sampling-based RBDO capability by using a classification method, VSVM. These are new capabilities that have been successfully published in archived journals.

Technology transfer: Updated SS-DKG (ARO funding), Copula (TARDEC funding), and sampling-based RBDO (TARDEC funding) with easy-to-use user interface incorporated into the PI's Iowa-RBDO (I-RBDO) code. These are integrated in Iowa RBDO (I-RBDO) software system that has been delivered to TARDEC (Dr. David Lamb). During the summer of 2012, I-RBDO was installed on TARDEC's High Performance Computing (HPC) system and Mr. Nick Gaul, who is one of the Professor K.K. Choi's Ph.D. students, worked as an intern with TARDEC scientists to successfully apply I-RBDO to several Army application problems.

PI's research team assisted Dr. David Lamb in TARDEC's proposal for a Dedicated Support Partition (DSP) on Army Research Laboratory's (ARL) HPC system, which provides 2304 cores with 4GB/core and 20.2 Million CPU hours per year for two years to install I-RBDO exclusively and demonstrate applications for Army ground vehicle design problems. In June 2013, the new DSP was awarded to TARDEC. In August 2013, a small company, RAMDO Solutions, LLC, was established and the research software I-RBDO was delivered so that the company can develop a commercial software Reliability Analysis & Multidisciplinary Design Optimization (RAMDO). RAMDO will be eventually installed to DSP for TARDEC's use. For commercialization, two leading PIDO developers, Altair and Dassault Simulia, agreed with RAMDO Solutions, LLC to integrate our RAMDO with their

PIDO softwares – HyperStudy and Isight – respectively.

Technology Transfer