Research Contributions

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Research Works

2019–2020 **Variational Optimization of Informational Privacy**

The datasets containing sensitive information can't be publicly shared as a privacy-risk posed by several types of attacks exists. The data perturbation approach uses a random noise adding mechanism to preserve privacy, however, results in distortion of useful data. There remains the challenge of studying and optimizing privacy-utility tradeoff especially in the case when statistical distributions of data are unknown. This study introduces a novel information theoretic framework for studying privacy-utility tradeoff suitable for multivariate data and for the cases with unknown statistical distributions. We consider an information theoretic approach of quantifying privacy-leakage by the mutual information between sensitive data and released data. At the core of privacy-preserving framework lies a variational Bayesian fuzzy model approximating the uncertain mapping between released noise added data and private data such that the model is employed for variational approximation of informational privacy. The suggested privacy-preserving framework consists of three components: 1) Optimal Noise Adding Mechanism; 2) Modeling of Uncertain Mapping Between Released Noise Added Data and Private Data; and 3) Variational Approximation of Information Privacy.

Publications

M. Kumar, D. Brunner, B. A. Moser, and B. Freudenthaler, "Variational Optimization of Informational Privacy," In: Kotsis G. et al. (eds): *Database and Expert Systems Applications. DEXA 2020. Communications in Computer and Information Science*. vol 1285. Springer, Cham.

Research area **Privacy-Preserving Machine Learning**

2019–2020 **An Explainable Fuzzy Theoretic Nonparametric Deep Model for Stress Assessment Using Heartbeat Intervals Analysis**

This study presents an explainable fuzzy theoretic nonparametric deep model for an analysis of heart rate variability in application to stress assessment. We are concerned with the development of a model that evaluates and explains a short-time (3-5 minutes long) heartbeat interval sequence of an individual to estimate the level of acute perceived stress on a numerical scale from 0 to 100 via monitoring the functioning of the autonomic nervous system. The salient features of the approach are: a) A deep model, consisting of a nested composition of mappings, discovers layers of increasingly abstract heartbeat interval data representation. b) An analytical solution of the deep model's learning problem facilitates inducing a mapping from the non-interpretable heartbeat-interval-data-space onto another *interpretable* domain spanned by a stress index. A given non-interpretable R-R interval feature vector is explained by a) estimating the corresponding stress value, b) providing the weights which must be assigned to the subjective ratings of stress, and c) providing various information about the sympathetic and parasympathetic activities of autonomic nervous system by analyzing R-R interval sequence in frequency domain at different abstraction levels. The proof-of-concept is provided by experimentation on a previously studied dataset of 50 subjects and a new dataset of 100 subjects.

Publications

M. Kumar, W. Zhang, M. Weippert, and B. Freudenthaler, "An Explainable Fuzzy Theoretic Nonparametric Deep Model for Stress Assessment Using Heartbeat Intervals Analysis," *IEEE Transactions on Fuzzy Systems*, doi: 10.1109/TFUZZ.2020.3029284.

Research area **Explainable Deep Learning**

2019–2020 **An Optimal (ϵ, δ)—Differentially Private Learning of Distributed Deep Fuzzy Models**

This study introduces a privacy-preserving framework for distributed deep fuzzy learning. Assuming training data as private, the problem of learning of local deep fuzzy models is considered in a distributed setting under differential privacy framework. A local deep fuzzy model, formed by a composition of a finite number of Takagi-Sugeno type fuzzy filters, is learned using variational Bayesian inference. This paper suggests an optimal (ϵ, δ)—differentially private noise adding mechanism that results in multi-fold reduction in noise magnitude over the classical Gaussian mechanism and thus leads to an increased utility for a given level of privacy. Further, the robustness feature, offered by the rule-based fuzzy systems, is leveraged to alleviate the effect of added data noise on the utility. An architecture for distributed form of differentially private learning is suggested where a privacy wall separates the private local training data from the globally shared data, and fuzzy sets and fuzzy rules are used to aggregate robustly the local deep fuzzy models for building the global model. The privacy wall uses noise adding mechanisms to attain differential privacy for each participant's private training data and thus the adversaries have no direct access to the training data.

Publications

M. Kumar, M. Rossbory, B. A. Moser, and B. Freudenthaler, "An Optimal (ϵ, δ)—Differentially Private Learning of Distributed Deep Fuzzy Models," *Information Sciences*, https://doi.org/10.1016/j.ins.2020.07.044.

M. Kumar, M. Rossbory, B. A. Moser, and B. Freudenthaler, "Differentially Private Learning of Distributed Deep Models," in *Proc. Adjunct Publication of the 28th ACM Conference on User Modeling, Adaptation and Personalization (UMAP '20 Adjunct)*, (Association for Computing Machinery, New York, NY, USA), pp. 193–200, July 2020.

Research area **Privacy-Preserving Machine Learning**

2019–2020 **Deep Gaussian Fuzzy-Mappings**

This study introduces a variational analysis approach to the learning of a deep model formed via a nested composition of mappings. The fuzzy sets, being characterized by Gaussian type of membership functions, are used to represent unknown functions associated to the layers of the model. The learning of the deep model would require a quantification of the uncertainties on the signals across the layers of the deep model. We derive analytically the mathematical expressions for membership functions using variational optimization to quantify the uncertainties on variables. The most significant feature of the learning approach is that all of the unobserved variables and parameters, associated to the deep model, are averaged out where the averages are computed taking into account the uncertainties (on variables and parameters). The uncertainties are quantified by means of fuzzy sets with membership functions optimally learned from the observed data. A rigorous mathematical treatment of the learning problem results in the development of a competitive classification algorithm. The study is a theoretical contribution to the field of fuzzy machine learning, nevertheless, offering practical machine learning algorithms.

Publications

M. Kumar, S. Singh, and B. Freudenthaler, "Gaussian fuzzy theoretic analysis for variational learning of nested compositions," *International Journal of Approximate Reasoning*, https://doi.org/10.1016/j.ijar.2020.12.021

Research area **Machine Learning**

2018–2019 **Membership Functional Analysis for Nonparametric Deep Models of Image Features**

The application of fuzzy theory to deep learning is limited 1) under the realm of deep neural networks; 2) to the parametric form of modeling; and 3) relying on gradient-descent based numerical algorithms for optimization because of lack of analytical solutions. This study fills this gap by providing an analytical nonparametric deep modeling solution based on the mathematical analysis of membership functions assigned to model variables. Our nonparametric approach is based on the concept of representing the unknown mappings (between input and output variables) through a fuzzy set with *Student-t* type membership function such that the dimension of membership function increases with an increasing data size. This concept of function representation is referred to as "*Student-t fuzzy-mapping*" in this study. The most significant feature of this paper is to analytically derive the mathematical expressions for membership functions (which quantify uncertainties regarding the values of variables) using variational optimization such that the degree-of-belongingness of given data to the considered data-model is maximized. The study focuses on the modeling of image features where a layer of the deep-model first projects the feature vector onto a lower dimensional subspace and then construct the output feature vector through Student-t fuzzy-mappings. Numerous image classification experiments are provided to support the proposed approach.

Publications

M. Kumar and B. Freudenthaler, "Fuzzy Membership Functional Analysis for Nonparametric Deep Models of Image Features," *IEEE Transactions on Fuzzy Systems*, https://doi.org/10.1109/TFUZZ.2019.2950636.

Research area **Deep Learning**

2018–2019 **Deriving an Optimal Noise Adding Mechanism for Privacy-Preserving Machine Learning**

This study introduces a privacy-preserving framework to fuzzy machine learning. Assuming training data as private, the problem of learning of local deep fuzzy models is considered in a distributed setting under differential privacy framework. A local deep fuzzy model, formed by a composition of a finite number of Takagi-Sugeno type fuzzy filters, is learned using variational Bayesian inference. This paper suggests an optimal (ϵ, δ)—differentially private noise adding mechanism that results in multi-fold reduction in noise magnitude over the classical Gaussian mechanism and thus leads to an increased utility for a given level of privacy. Further, the robustness feature, offered by the rule-based fuzzy systems, is leveraged to alleviate the effect of added data noise on the utility. An architecture for distributed form of differentially private learning is suggested where a privacy wall separates the private local training data from the globally shared data, and fuzzy sets and fuzzy rules are used to aggregate robustly the local deep fuzzy models for building the global model. The privacy wall uses noise adding mechanisms to attain differential privacy for each participant's private training data and thus the adversaries have no direct access to the training data.

Publications

M. Kumar, M. Rossbory, B. A. Moser, B. Freudenthaler, "Deriving an Optimal Noise Adding Mechanism for Privacy-Preserving Machine Learning," in *Proc. Database and Expert Systems Applications (DEXA 2019)*, (Linz, Austria), Aug. 2019.

Research area **Privacy-Preserving Machine Learning**

2017–2018 **Fuzzy Theoretic Model Based Analysis of Image Features**

Recently, fuzzy membership functions based image descriptors were introduced as competing alternative to the classical histograms based image descriptors. The design of a suitable mathematical criterion for matching image descriptors to detect the correspondences between the images remains as one of the basic problems of image matching and computer vision. This study extends fuzzy membership functions based algorithms to the mathematical analysis of the correspondences between descriptors of multiple images. To facilitate a fuzzy analysis of image descriptors, a fuzzy membership function on the descriptors is modeled as a finite mixture of the descriptor's memberships to different descriptor-prototypes. The so-defined fuzzy membership function involves parameter vectors with a special structure such that all elements of the vector are non-negatives and sum to unity. These parameter vectors are considered as uncertain and are modeled by Dirichlet type fuzzy membership functions. The fuzzy membership functions are determined analytically by solving a deterministic constrained optimization problem using variational optimization. The fuzzy membership functions based analysis leads to significantly more accurate and reliable multi-image matching algorithm that can be applied under different scenarios including that of *Collage* creation and fully automated image clustering.

Publications

M. Kumar, S. Chatterjee, W. Zhang, J. Yang, and L. M. Kolbe, "Fuzzy Theoretic Model Based Analysis of Image Features," *Information Sciences*, vol. 480, pp. 34-54, 2019.

Research area **Image Mining & Computer Vision**

2016–2017 **Fuzzy Theoretic Approach to Signals and Systems: Static Systems**

"*Fuzzy Theoretic Approach to Signals and Systems*" assumes all system variables and parameters as uncertain (i.e. being characterized by fuzzy membership functions), develops a mathematical theory for analytically determining the fuzzy membership functions on system variables and parameters, derives algorithms for estimating the parameters of fuzzy membership functions, and establishes robustness and convergence properties of the estimation algorithms. The fuzzy membership functions are analytically determined by solving a variational optimization problem that maximizes the "*over-uncertainties-averaged-log-membership*" of the observed data around an initial guess. This study develops the analytical fuzzy theory for the particular case of a multi-input single-output static system being affected by noises. The theory facilitates designing an adaptive filtering algorithm. The robustness of the adaptive filtering algorithm is proved theoretically via a mathematical analysis. Numerical experiments further demonstrate the robustness of the filtering algorithm. A comparison of the algorithm with the state-of-art methods is made by considering the practical biomedical applications related to the modeling and analysis of heart rate signals for assessing the physiological state of an individual.

Publications

M. Kumar, Y. Mao, Y. Wang, T. Qiu, Y. Chenggen, and W. Zhang, "Fuzzy theoretic approach to signals and systems: Static systems," *Information Sciences*, vol. 418-419, pp. 668-702, 2017.

Research area **Signal & System Theory**

2016–2017 **Analyticallly Derived Fuzzy Membership Functions**

The numerical algorithms typically used for determining the fuzzy membership functions are inexact, slow, and lack in the mathematical theory. This study suggests an analytical approach to the determination of fuzzy membership functions by using the variational optimization method. The uncertain parameters of a membership function are modeled by variational-membership-functions. The optimal expressions for variational-membership-functions are derived by maximizing analytically the log-membership of the data samples. The uncertain parameters are then averaged over the derived optimal variational-membership-functions leading to the so-called optimal determination of the membership function. Several different scenarios of the uncertain variables are built up and the membership function is designed in each scenario analytically. The application potential of the methodology is demonstrated by studying a biomedical signal analysis problem. Another practical application is concerned with the image matching and imaging based personal identification. This study and more studies in this direction will pave the way for the fuzzy researchers to reduce their dependance on numerical algorithms by designing the fuzzy systems in a more analytical manner.

Publications

W. Zhang, M. Kumar, Y. Zhou, J. Yang, and Y. Mao, "Analytically derived fuzzy membership functions," *Cluster Computing*, 2017, https://doi.org/10.1007/s10586-017-1503-2.

Research area **Fuzzy Systems & Variational Optimization**

2016–2017 **An Adaptive Fuzzy Filter for Image Denoising**

This study considers the problem of fuzzy modeling of the images in pixel domain. A zero-order Takagi-Sugeno type fuzzy model provides fuzzy smoothing to the image intensities for removing the additive noise from an image. An adaptive fuzzy filtering algorithm is suggested for estimating the parameters of the fuzzy model with noisy image data. The mathematical analysis of the proposed filtering algorithm has been provided in both deterministic and stochastic framework. The deterministic robustness of the filtering algorithm was shown by deriving an upper bound on the magnitude of estimation errors. The fuzzy filtering algorithm doesn't demand Gaussian assumption of the noise and is also optimal in the "*sense*" of variation Bayes towards Student-t distributed noises.

Publications

W. Zhang, M. Kumar, J. Yang, Y. Zhou, and Y. Mao, "An adaptive fuzzy filter for image denoising," *Cluster Comput*, 2018, https://doi.org/10.1007/s10586-018-2253-5

Research area **Image Processing & Fuzzy Filtering**

2013–2014 **Fuzzy Memberships Descriptors for Images**

The fuzzy membership functions based local image descriptors are introduced as a competing alternative to widely accepted histograms based image descriptors. The fuzzy memberships descriptors are highly distinctive and thus facilitate an accurate image matching. This work utilizes fuzzy memberships descriptors to design a method meant for image matching. The method finds the correspondence between the two images. The study also introduces *Gamma mixture fuzzy model* for detecting geometrically consistent correspondence between the two images. The Gamma mixture fuzzy model combines a finite number of Gamma distributions through a fuzzy model. The parameters of Gamma mixture fuzzy model are inferred by a method similar to the variational Bayes. The image matching examples provided in the text support the claim of fuzzy memberships descriptors being highly distinctive. The method was also applied on 2D ear images for an automated human identification. The experimental results achieved the rank-one recognition accuracy of 97.5659% on a database of 125 subjects containing 493 ear images. The motivation of this study is derived from the application potential of fuzzy membership functions in characterizing the local image features.

Publications

M. Kumar, N. Stoll, K. Thurow, and R. Stoll, "Fuzzy Memberships Descriptors for Images," *IEEE Transactions on Fuzzy Systems*, vol. 24, no. 1, pp. 195-207, 2016.

Research area **Computer Vision & Image Processing**

2013–2014 **A Stochastic Framework for Robust Fuzzy Filtering and Analysis of Signals**

This study presents a unified stochastic framework meant for signal modeling as well as analysis. The signals are modeled via linear-in-parameters models (e.g. a type of Takagi-Sugeno fuzzy model) based on variational Bayes methodology. This gives rise to the "negative free energy maximizing" filtering algorithm. The work presented here highlighted that it was analytically possible to maximize the information theoretic quantity, "mutual information", exactly in the same manner as maximizing "negative free energy" in variational Bayes methodology. This gives rise to the "variational information maximizing" analysis algorithm. The robustness of the methodology against data outliers is achieved by modeling the noises with Student-t distributions. The framework takes into account the inputs' noises as well apart from the usually considered output noise. The robustness of the adaptive filtering algorithm against noise is shown by a deterministic analysis where an upper bound on the magnitude of estimation errors is derived.

The work provides several applications scenarios of introduced signals' modeling and analysis framework to solve the practical problems. Some of the challenging practical problems related to signal/data processing have been formulated in a manner that the "negative free energy maximizing" filtering and "variational information maximizing" analysis algorithms could be directly applied to solve the problems. The studied application examples include robust comparison of objects' geometries in images for child ear biometrics, biomedical signals classification, data smoothing for reflection-mode ultrasound imaging, and modeling related applications. The application examples support the mathematical theory by providing just the "proof-of-concept".

Publications

M. Kumar, N. Stoll, R. Stoll, and K. Thurow, "A Stochastic Framework for Robust Fuzzy Filtering and Analysis of Signals - Part I," *IEEE Transactions on Cybernetics*, vol. 46, no. 5, pp. 1118-1131, 2016.

M. Kumar, N. Stoll, R. Stoll, and K. Thurow, "A Stochastic Framework for Robust Fuzzy Filtering and Analysis of Signals - Part II," *IEEE Transactions on Cybernetics*, vol. 45, no. 3, pp. 486-496, 2015.

Research area **Stochastic Modeling & Analysis**

2012–2013 **Mobile Phone Based Child Biometrics for Improved Immunization**

This study develops the concept of mobile phone based ear biometrics for young children. An interactive user friendly android based mobile application, named "CuteEars", was developed for biometrics identification of young children and for a reliable documentation of the routine immunization events in rural India. This simple easy to use efficient software installed on an android cell phone will be used for maintaining the database of administering of vaccination to a recipient child. Any previous related history, if applicable, of the immunization and other basic details of the recipient child will also be recorded. To extract the required biometric information from the ear picture of child posed a great challenge. While the standard biometrics techniques typically operate on the pictures taken under controlled conditions, new image processing algorithms were developed capable of performing biometrics even under non-standard conditions such as different light intensities, the presence of unwanted objects (like hair, cloth fabric) in the ear photo, a difference in the angular position of ear, and so on. To meet this challenge, the advanced computational intelligence based signal modeling and analysis techniques have been exploited to develop image processing algorithms meant for a "robust" comparison of objects' geometries in images. The developed intelligent ear biometrics technology has been integrated to function with the android mobile application, "CuteEars", by Hanseatic Institute of Technology, Germany. The concept was validated on 750 children by a team formed by Shah Satnamji Green-S Welfare Force Wing, India.

Publications

M. Kumar, A. Insan, N. Stoll, K. Thurow, and R. Stoll, "Fuzzy Models for Ear Imaging Based Identification of Infants and Young Children," *IEEE Transactions on Systems, Man and Cybernetics: Systems*, vol. 46, no. 9, pp. 1265-1278, 2016.

Research area **mHealth & Biometrics**

2011–2012 **Stationary Fuzzy Fokker-Planck Learning**

Stationary fuzzy Fokker-Planck learning (SFFPL) is a recently introduced computational method that applies fuzzy modeling to solve optimization problems. This study develops a concept of applying SFFPL based computations for nonlinear constrained optimization.We consider the development of SFFPL based optimization algorithms which don't require derivatives of the objective function and of the constraints. The sequential penalty approach was used to handle the inequality constraints. It was proved under some standard assumptions that the carefully designed SFFPL based algorithms converge asymptotically to the stationary points. The convergence proofs follow a simple mathematical approach and invoke mean-value theorem. The algorithms were evaluated on the test problems with the number of variables up to 50. The performance comparison of the proposed algorithms with some of the standard optimization algorithms further justifies our approach. The SFFPL based optimization approach, due to its novelty, could be possibly extended to several research directions.

Publications

M. Kumar, N. Stoll, K. Thurow, and R. Stoll, "Stationary Fuzzy Fokker-Planck Learning for Derivative-Free Optimization," *IEEE Transactions on Fuzzy Systems*, vol. 21, no. 2, pp. 193-208, 2013.

Research area **Optimization**

2010–2011 **Stress Monitoring Based on Stochastic Fuzzy Analysis of Heartbeat Intervals**

Quantifying stress levels of an individual based on a mathematical analysis of real-time physiological data measurements is challenging. This study suggests a stochastic fuzzy analysis method to evaluate the short time series of R-R intervals for a quantification of the stress level. The five minutes long series of R-R intervals recorded under a given stress level are modeled by a stochastic fuzzy system. The stochastic model of heartbeat intervals is individual specific and corresponds to a particular stress level. Once the different heartbeat intervals models are available for an individual, an analysis of the given R-R interval series generated under an unknown stress level is performed by a stochastic interpolation of the models. The stress estimation method has been implemented in a mobile telemedical application employing an e-health system for an efficient and cost-effective monitoring of patients while being at home or practicing their daily jobs. The experiments involve 50 individuals whose stress scores were assessed at different times of the day. The subjective rating scores showed a high correlation with the values predicted by proposed analysis method.

Publications

M. Kumar, S. Neubert, S. Behrendt, A. Rieger, M. Weippert, N. Stoll, K. Thurow, and R. Stoll, "Stress Monitoring Based on Stochastic Fuzzy Analysis of Heartbeat Intervals," *IEEE Transactions on Fuzzy Systems*, vol. 20, no. 4, pp. 746-759, 2012.

Research area **Biomedical Signal Analysis**

2010–2011 **Stationary Fuzzy Fokker-Planck Learning and Stochastic Fuzzy Filtering**

The application of nonlinear optimization to the estimation of fuzzy model parameters is well known. For doing reverse of this, the concept of SFFPL (stationary fuzzy Fokker-Planck learning) is introduced i.e. SFFPL applies the fuzzy modeling technique in nonlinear optimization problems. SFFPL is based on the fuzzy approximation of stationary probability density of a stochastic search process associated to the nonlinear optimization problem. A carefully designed algorithm is suggested for SFFPL to locate the optimum point.

We consider the variational Bayes (VB) based inference of a stochastic fuzzy filter whose consequents as well as the antecedents are random variables. The problem of VB inference of stochastic antecedents, due to the nonlinearity of likelihood function, is analytically intractable. The SFFPL algorithm for high dimensional nonlinear optimization, that doesn't require the derivative of the objective function, can be used for numerically solving the stochastic fuzzy filtering problem.

Publications

M. Kumar, N. Stoll, and R. Stoll, "Stationary Fuzzy Fokker-Planck Learning and Stochastic Fuzzy Filtering," *IEEE Transactions on Fuzzy Systems*, vol. 19, no. 5, pp. 873-889, 2011.

Research area **Stochastic Fuzzy Filtering**

2009–2010 **Variational Bayes for a Mixed Stochastic/Deterministic Fuzzy Filter**

This study, under variational Bayes (VB) framework, infers the parameters of a Takagi-Sugeno fuzzy filter having deterministic antecedents and stochastic consequents. The motivation of the study is to take advantages of the VB framework in designing fuzzy filtering algorithms. These advantages include an automated regularization, incorporation of statistical noise models, and model comparison capability. The VB method can be easily applied to the linear-in-parameters models. This work applies VB method to the nonlinear fuzzy filters without using Taylor expansion for a linear approximation of some nonlinear function. It is assumed that the nonlinear parameters (i.e. antecedents) of the fuzzy filter are deterministic while linear parameters are stochastic. The VB algorithm, by maximizing a strict lower bound on the data evidence, makes the approximate posterior of linear parameters as close to the true posterior as possible. The nonlinear deterministic parameters are tuned in a way to further increase the lower bound on data evidence. The VB paradigm can be used to design an algorithm that automatically selects the most suitable fuzzy filter out of the considered finite set of fuzzy filters. This is done by fitting the observed data as a stochastic combination of the different Takagi-Sugeno fuzzy filters such that the individual filters compete with one another to model the data.

Publications

M. Kumar, N. Stoll, and R. Stoll, "Variational Bayes for a Mixed Stochastic/Deterministic Fuzzy Filter," *IEEE Transactions on Fuzzy Systems*, vol. 18, no. 4, pp. 787-801, 2010.

Research area **Variational Bayesian Analysis**

2009–2010 **A Mixture of Fuzzy Filters Applied to the Analysis of Heartbeat Intervals**

This study provides a stochastic modeling of the heartbeat intervals using a mixture of Takagi-Sugeno type fuzzy filters. The model parameters are inferred under variational Bayes (VB) framework. The model of the heartbeat intervals is in the form of a history-dependent probability density. The parameters, characterizing the heartbeat intervals probability density, include the estimated parameters of different fuzzy filters and may serve as the features of the heartbeat interval series. The features of the heartbeat intervals provide a description of the physiological state of an individual. A novelty of our analysis method is that the physiological state is predicted as a part of the features extraction procedure. This is done via deriving, using VB paradigm, an analytical expression for the posterior distribution that the observed heartbeat intervals have been generated by the stochastic model of the physiological state.

Publications

M. Kumar, M. Weippert, N. Stoll, and R. Stoll, "A Mixture of Fuzzy Filters Applied to the Analysis of Heart Beat Intervals," *Fuzzy Optimization and Decision Making*, vol. 9, no. 4, pp. 383-412, 2010.

Research area **Stochastic Fuzzy Systems**

2008–2009 **Fuzzy Filtering for Physiological Signal Analysis**

This study suggests the use of fuzzy filtering algorithms to deal with the uncertainties associated to the interpretation of analysis of physiological signals. The signal characteristics, for a given situation or physiological state, vary for an individual over time and also vary among the individuals with the same state. These random variations are due to the several time-varying factors related to the physiological behavior of individuals which can't be taken into account in the interpretation of signal characteristics for solving a medical decision making problem. The approach is to reduce the effect of random variations on the analysis of signal characteristics via filtering out randomness or uncertainty from the signal using a nonlinear fuzzy filter.

Publications

M. Kumar, M. Weippert, D. Arndt, S. Kreuzfeld, K. Thurow, N. Stoll, R. Stoll, "Fuzzy Filtering for Physiological Signal Analysis," *IEEE Transactions Fuzzy Systems*, vol. 18, no. 1, pp. 208-216, 2010.

Research area **Biomedical Signal Processing**

2007–2008 **Bioconcentration Factor Modeling**

This work presented a fuzzy filtering based technique for rendering robustness to the modeling methods. A case study, dealing with the development of a model for predicting the bioconcentration factor (BCF) of chemicals, was considered. The conventional neural/fuzzy BCF models, due to the involved uncertainties, may have a poor generalization performance (i.e. poor prediction performance for new chemicals). The approach to improve the generalization performance of neural/fuzzy BCF models consists of 1) exploiting a fuzzy filter to filter out the uncertainties from the modeling problem, 2) utilizing the information about uncertainties, being provided by the fuzzy filter, for the identification of robust BCF models with an increased generalization performance. The approach was illustrated with a data set of 511 chemicals taking different types of neural/fuzzy modeling techniques.

Publications

S. Kumar, M. Kumar, K. Thurow, R. Stoll, and U. Kragl, "Fuzzy filtering for robust bioconcentration factor modelling," *Environmental Modelling & Software*, vol. 24, no. 1, pp. 44-53, 2009.

Research area **Environmental Modeling**

2006–2007 **Fuzzy Modeling of Subjective Workload Score**

This project was concerned with the development of a computer model to estimate the subjective workload score of individuals by evaluating the heart rate signals. The identification of a model to estimate subjective workload score of individuals under different workload situations is a too ambitious task since different individuals (due to different body conditions, emotional states, age, gender, etc.) show different physiological response (assessed by evaluating heart rate signal) under different workload situations. This is equivalent to say that the mathematical mappings between physiological parameters and workload score are uncertain. Our approach to deal with the uncertainties in workload modeling problem consists of following steps: 1) The uncertainties, arising due the individual variations in identifying a common model valid for all the individuals, are filtered out using a fuzzy filter. 2) Stochastic modeling of the uncertainties (provided by the fuzzy filter) using finite mixture models and utilizing this information regarding uncertainties for identifying the structure and initial parameters of a workload model. 3) Finally, the workload model parameters, for an individual, are identified in an online scenario using machine learning algorithms. The contribution of the study was to propose, with a mathematical analysis, a fuzzy based modeling technique that first filters out the uncertainties from the modeling problem, analyzes the uncertainties statistically using finite mixture modeling, and finally the information about uncertainties is utilized for adapting the workload model to an individual's physiological conditions. This approach, demonstrated with the real-world medical data of 11 subjects, provided a fuzzy based tool useful for modeling in presence of uncertainties.

Publications

M. Kumar, D. Arndt, S. Kreuzfeld, K. Thurow, N. Stoll, and R. Stoll, "Fuzzy techniques for subjective workload score modelling under uncertainties," *IEEE Transactions on Systems, Man, and Cybernetics-Part B: Cybernetics*, vol. 38, no. 6, pp. 1449-1464, 2008.

Research area **Ergonomics & Operator Assessment**

2006–2007 **Toxicity Modeling**

A fundamental concern in the Quantitative Structure-Activity Relationship approach to toxicity evaluation is the generalization of the model over a wide range of compounds. The data driven modeling of toxicity, due to the complex and ill-defined nature of eco-toxicological systems, is an uncertain process. The development of a toxicity predicting model without considering uncertainties may produce a model with a low generalization performance. This work presented a novel approach to toxicity modeling that handles the involved uncertainties using a fuzzy filter, and thus improves the generalization capability of the model. The method was illustrated by considering a data set built up by U.S. Environmental Protection Agency referring to acute toxicity 96-h LC_{50} in the fathead minnow fish (*Pimephales promelas*). The data set contains 568 compounds representing several chemical classes and modes of action.

Publications

S. Kumar, M. Kumar, R. Stoll, and U. Kragl, "Handling uncertainties in toxicity modelling using a fuzzy filter," *SAR and QSAR in Environmental Research*, vol. 18, no. 7-8, pp. 645-662, 2007.

Research area **Environmental Modeling**

2001–2007 **Fuzzy Filtering**

To deal with the real-world problems characterized by complexities and uncertainties, the design of the fuzzy filters is an important issue since the real-world applications require the filtering of uncertainties from the experimental data. Therefore, we developed a mathematical framework for the design and analysis of fuzzy based intelligent systems taking into account the underlying uncertainties in a sensible way. This framework facilitate the design of algorithms optimized for performance and complexity making them suitable for a real-time operation. Fuzzy filtering algorithms, i.e. the strategies for estimating the parameters of a nonlinear fuzzy filter, were developed based on different mathematical criteria. The studied mathematical criteria include

1. Robust Regularized Least-Squares Estimation
2. $H^{\infty}-$optimal Estimation
3. Least-Squares Estimation
4. Generalized Least-mean-squares like $p-$norm Algorithms
5. Risk-sensitive Estimation

A mathematical theory was developed for the stability, robustness, and steady-state analyses of fuzzy filtering algorithms.

Publications

M. Kumar, R. Stoll, and N. Stoll, "A robust design criterion for interpretable fuzzy models with uncertain data," *IEEE Trans. on Fuzzy Systems*, vol. 14, pp. 314-328, Apr. 2006.

M. Kumar, R. Stoll, and N. Stoll, "A min-max approach to fuzzy clustering, estimation, and identification," *IEEE Trans. on Fuzzy Systems*, vol. 14, pp. 248-262, Apr. 2006.

M. Kumar, N. Stoll, and R. Stoll, "An energy-gain bounding approach to robust fuzzy identification," *Automatica*, vol. 42, pp. 711-721, May 2006.

M. Kumar, R. Stoll, and N. Stoll, "Deterministic approach to robust adaptive learning of fuzzy models," *IEEE Trans. Syst., Man., Cybern. B*, vol. 36, pp. 767-780, Aug. 2006.

M. Kumar, N. Stoll, and R. Stoll, "Adaptive fuzzy filtering in a deterministic setting," *IEEE Transactions on Fuzzy Systems*, vol. 17, no. 4, pp. 763-776, Aug. 2009.

M. Kumar, N. Stoll, and R. Stoll, "On the estimation of parameters of takagi-sugeno fuzzy filters," *IEEE Transactions on Fuzzy Systems*, vol. 17, no. 1, pp. 150-166, Feb. 2009.

Research area **Estimation & Adaptive Filtering**

2005–2006 **Fuzzy Models for Quantitative Structure-Activity Relationship (QSAR)**

An important issue in QSAR modeling is of robustness, i.e., model should not undergo overtraining and model performance should be least sensitive to the modeling errors associated with the chosen descriptors and structure of the model. The method studied in this project established a robust input-output mappings for QSAR studies based on fuzzy "if-then" rules. The identification of these mappings (i.e. the construction of fuzzy rules) is based on a robust criterion being referred to as "energy-gain bounding approach". The method minimizes the maximum possible value of energy-gain from modeling errors to the identification errors. The maximum value of energy-gain (that will be minimized) is calculated over all possible finite disturbances without making any statistical assumptions about the nature of signals. A comparison of the method with Bayesian regularized neural networks was provided through the QSAR modeling examples of 1) carboquinones data set, 2) benzodiazepine data set, and 3) predicting the rate constant for hydroxyl radical tropospheric degradation of 460 heterogeneous organic compounds.

Publications

M. Kumar, K. Thurow, N. Stoll, and R. Stoll, "Robust fuzzy mappings for QSAR studies," *European Journal of Medicinal Chemistry*, vol. 42, pp. 675-685, 2007.

Research area **Chemistry & Drug Design**

2004–2006 **Fuzzy Filtering Based Mental Stress Assessment**

This project presented a novel method of heart rate signal analysis for stress assessment using fuzzy clustering and robust identification techniques. The emphasis of this study was to handle the uncertainties, arising due to a difference in the physiological behavior of individuals (because of different body conditions, age, gender, and so on), using a fuzzy model. The experiments involved 38 physically fit subjects (26 male, 12 female, aged 18-29 years) in air traffic control task simulations. The subjective rating scores of mental workload were assessed using NASA Task Load Index. Fuzzy clustering methods were used to model the experimental data. Further, a robust fuzzy identification technique was used to handle the uncertainties due to individual variations for the assessment of mental stress.

Publications

M. Kumar, M. Weippert, R. Vilbrandt, S. Kreuzfeld, and R. Stoll, "Fuzzy evaluation of heart rate signals for mental stress assessment," *IEEE Trans. on Fuzzy Systems*, vol. 15, no. 5, pp. 791-808, 2007.

Research area **Biomedical Data Modeling & Analysis**

2001–2004 **Fuzzy Estimation of Physical Fitness**

Occupational Medicine encompasses issues such as determination of job requirements, assessing individuals, and monitoring their performance over time. The involved complexities and uncertainties in the field of Occupational Medicine motivate us to use the fuzzy methodologies in handling the complicated optimization and decision making problems. As an application example of the developed Robust Fuzzy Estimation Theory, the problem of estimating the physical fitness of an individual, based on *intelligent* interpretation of ergo-spirometric data, was considered. The process of estimating physical fitness is uncertain due to 1) the uncertainties involved in the measurements of different physiological parameters and 2) the fact that different patients have different physiological behavior toward exercise testing. We considered the development of an expert system that quantifies the physical fitness level of an individual on a virtual scale ranging from zero to one. Such a quantitative description of physical fitness is useful even for the non-medical-experts without being involved in the complex physiology of exercise testing. Further, the functionality of the expert system is clearly understood by the user.

Publications

M. Kumar, R. Stoll, and N. Stoll, "Robust adaptive fuzzy identification of time-varying processes with uncertain data. Handling uncertainties in the physical fitness fuzzy approximation with real world medical data: An application," *Fuzzy Optimization and Decision Making*, vol. 2, no. 3, pp. 243-259, Sep. 2003.

M. Kumar, R. Stoll, and N. Stoll, "Regularized adaptation of fuzzy inference systems. Modelling the opinion of a medical expert about physical fitness: An application," *Fuzzy Optimization and Decision Making*, vol. 2, no. 4, pp. 317-336, Dec. 2003.

M. Kumar, R. Stoll, and N. Stoll, "Robust solution to fuzzy identification problem with uncertain data by regularization. Fuzzy approximation to physical fitness with real world medical data: An application," *Fuzzy Optimization and Decision Making*, vol. 3, no. 1, pp. 63-82, Mar. 2004.

M. Kumar, R. Stoll, and N. Stoll, "Robust adaptive identification of fuzzy systems with uncertain data," *Fuzzy Optimization and Decision Making*, vol. 3, no. 3, pp. 195-216, Sep. 2004.

Research area **Preventive Medicine**