Training Knowledge Bots for Physics-Based Simulations Using Artificial Neural Networks

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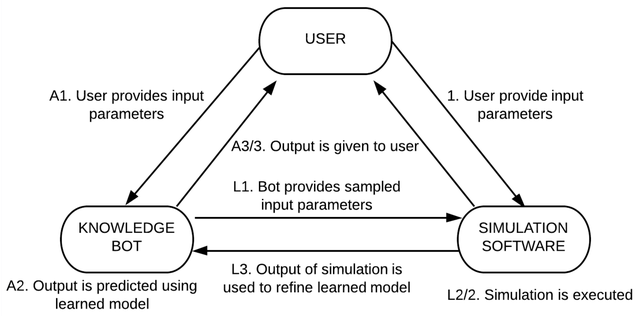
Motivation



- Millions of complex physics-based simulations by trained experts are required during design phase of aerospace vehicle
- *Knowledge bot* can capture underlying idiosyncrasies of simulation software to predict outcomes
- Train knowledge bot using artificial neural networks and treat simulation software as black-box to interrogate output values

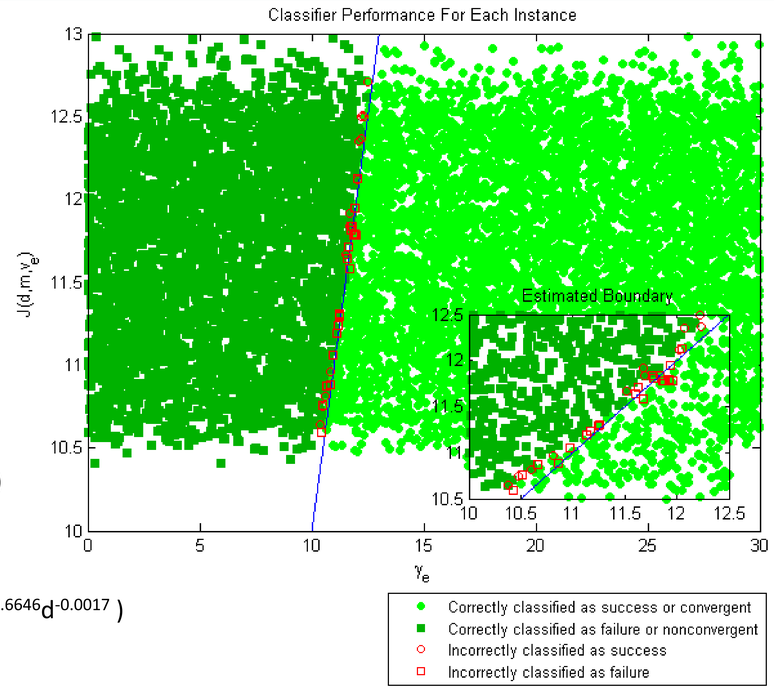
Relevant Work

- Artificial neural networks widely popular in 1940s analogized as "physical cellular systems which acquire, store, and utilize experimental knowledge"
- Multilayer Perception (MLP) network, where each node takes in a set of input parameters and computers output value, fed to nodes further down layer hierarchy as input
- Neural networks widely used for classification and prediction; multilayer feed-forward networks are universal approximators and have many applications,
    1. Controls of robot manipulators and nonlinear systems
    2. Motion planning
    3. Computer Vision and face detection
    4. Chemistry, prediction of secondary protein structures
    5. Clinical Medicine
    6. Finance, bankruptcy prediction
- GPU implementation of artificial neural networks for pattern recognition shown to be largely parallelizable
- Various approaches to understanding complex datasets using dimension reduction and data visualization when using artificial neural network machine learning

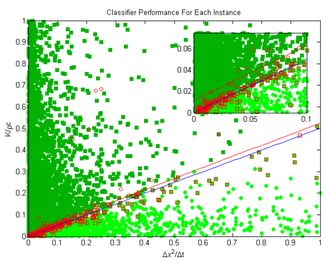
Demonstration

Trajectory Analysis (POST2):

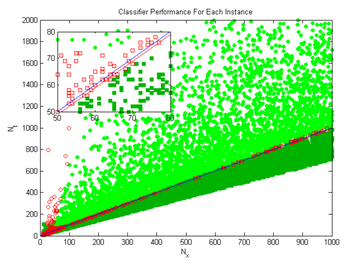
- Direct entry of 45-degree sphere-cone into Venus
- Input parameters include diameter, mass, entry flight path angle, entry velocity (d, m, v_e, γ_e)
- Classification plot illustrates predictions of classifier and actual simulation solution
- Describe boundary using $J(\cdot)$ via support vector machine
- Expression for boundary
  $J(d,m,v_e) = 0.0219 m^{0.0096} v_e^{0.6646} d^{-0.0017}$)



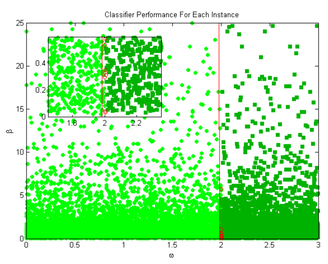
Other Simulation Classifications:



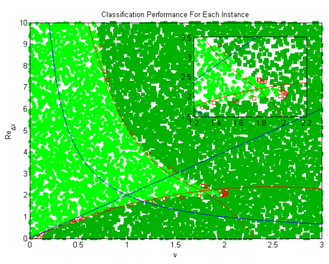
Parabolic 1D-heat equation



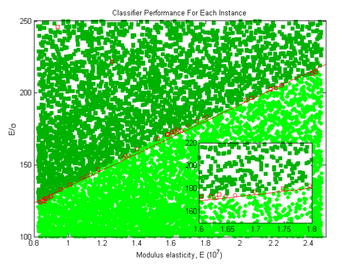
Hyperbolic-wave equation



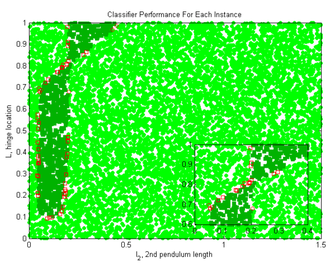
Elliptic-Laplaces' equation



Convective-Burgers' equation

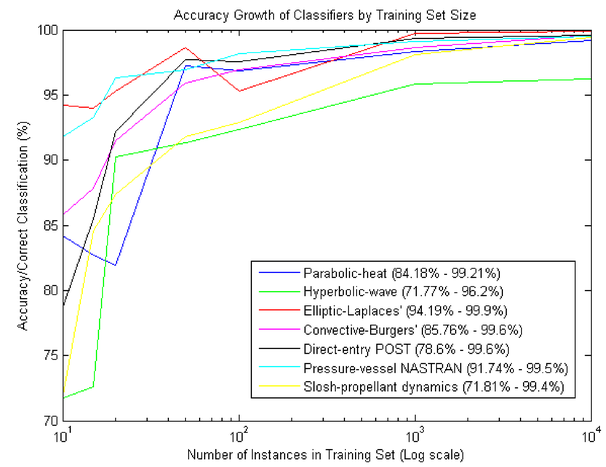


Pressure-vessel design (NASTRAN)



Slosh propellant Dynamics

Conclusion



- Artificial neural networks can be used to learn underlying properties of physics-based simulations; support vector machine can be used to describe clear boundary of multidimensional data
- All classifiers are over 99% accurate (hyperbolic-wave 96%), with only 10 instances mean accuracy ~80%, with 100 instances, 90%

References

[1] McCulloch, Warren; Walter Pitts (1943). "A Logical Calculus of Ideas Immanent in Nervous Activity". Bulletin of Mathematical Biophysics 5 (4): 115133.
[2] Rosenblatt, F. (1958). "The Perceptron: A Probalistic Model For Information Storage And Organization In The Brain". Psychological Review 65 (6): 386408.
[3] Zurada, J. Introduction to Artificial Neural Systems. 0-314-93391-3. West Publishing Co. 1992.
[4] I.H. Witten et al., Data Mining: Practical Machine Learning Tools and Techniques (3rd ed.), Burlington, MA: Elsevier Inc., 2011.
[5] Kurt Hornik, Maxwell B. Stinchcombe, Halbert White: Multilayer feedforward networks are universal approximators. Neural Networks 2(5): 359-366 (1989).
[6] Lewis, F. W., Suresh Jagannathan, and A. Yesildirak. Neural network control of robot manipulators and non-linear systems. CRC Press, 1998.
[7] Ge, Shuzhi S., and Christopher J. Harris. Adaptive neural network control of robotic manipulators. World Scientific Publishing Co., Inc., 1998.
[8] Yang, Simon X., and Max Meng. "An efficient neural network approach to dynamic robot motion planning." Neural Networks 13.2 (2000): 143-148.
[9] Rowley, Henry A., Shumeet Baluja, and Takeo Kanade. "Neural network-based face detection." Pattern Analysis and Machine Intelligence, IEEE Transactions on 20.1 (1998): 23-38.
[10] Golomb, Beatrice A., David T. Lawrence, and Terrence J. Sejnowski. "SENXET: A Neural Network Identifies Sex From Human Faces." NIPS. 1990.
[11] Holley, L. Howard, and Martin Karplus. "Protein secondary structure prediction with a neural network." Proceedings of the National Academy of Sciences 86.1 (1989): 152-156.
[12] Baxt, William G. "Application of artificial neural networks to clinical medicine." The lancet 346.8983 (1995): 1135-1138. [13] Azoff, E. Michael. Neural network time series forecasting of financial markets. John Wiley & Sons, Inc., 1994.
[14] Odom, M.D.; Sharda, R., "A neural network model for bankruptcy prediction," Neural Networks, 1990., 1990 IJCNN International Joint Conference on , vol., no., pp.163,168 vol.2, 17-21 June 1990.
[15] Ahn, B. S., S. S. Cho, and C. Y. Kim. "The integrated methodology of rough set theory and artificial neural network for business failure prediction." Expert Systems with Applications 18.2 (2000): 65-74.
[16] D. C. Ciresan, U. Meier, J. Masci, J. Schmidhuber. Multi-Column Deep Neural Network for Traffic Sign Classification. Neural Networks, 2012.
[17] Liles, C. Neural Network Machine Learning and Dimensional Reduction for Data Visualization. NASA/TM-2014-218181. 2014.
[18] Loret, Benjamin. "Classication of partial dierential equations into elliptic, parabolic and hyperbolic types". 12 Dec 2008.
[19] W. Chenney and D. Kincaid. Numerical Mathematics and Computing, 2nd ed. Pacific Grove, California: Brooks/Cole Publishing Company. 1985.
[20] F. M. White. Heat and Mass Transfer. Reading Massachusetts: Addison-Wesley Publishing Company. 1988.
[21] H. Carslaw and J. Jaeger. Conduction of Heat in Solids. 2nd ed. Oxford at the Clarendon Press. 1959.
[22] Patrick J. Roache. Computational Fluid Dynamics (1st ed.). Hermosa. 1972.
[23] D. A. Anderson, J. C. Tannehill, R. H. Pletcher. Computational Fluid Mechanics and Heat Transfer. New York: Hemisphere Publishing Corporation., 1984.
[24] F. J. Regan. S. M. Anandakrishnan. Re-Entry Vehicle Dynamics (AIAA Education Series). New York: American Institute of Aeronautics and Astronautics, Inc. ISBN 0-915928-78-7. 1984.
[25] Brauer, G. L., Cornick, D. E. and Stevenson, R., "Capabilities and Applications of the Program to Optimize Simulated Trajectories (POST), NASA CR-2770, Feb. 1977.
[26] Cortes, C.; Vapnik, V. (1995). "Support-vector networks". Machine Learning 20 (3): 273.
[27] Tong, Simon, and Daphne Koller. "Support vector machine active learning with applications to text classification." The Journal of Machine Learning Research 2 (2002): 45-66.
[28] Tong, Simon, and Edward Chang. "Support vector machine active learning for image retrieval." Proceedings of the ninth ACM international conference on Multimedia. ACM, 2001.
[29] Zhang, Lei, Fuzong Lin, and Bo Zhang. "Support vector machine learning for image retrieval." Image Processing, 2001. Proceedings. 2001 International Conference on. Vol. 2. IEEE, 2001.
[30] Hua, Sujun, and Zhirong Sun. "Support vector machine approach for protein subcellular localization prediction." Bioinformatics 17.8 (2001): 721-728.
[31] Cai, C. Z., et al. "SVM-Prot: web-based support vector machine software for functional classification of a protein from its primary sequence." Nucleic acids research 31.13 (2003): 3692-3697.
[32] Hua, Sujun, and Zhirong Sun. "A novel method of protein secondary structure prediction with high segment overlap measure: support vector machine approach." Journal of molecular biology 308.2 (2001): 397-407.
[33] Min, Jae H., and Young-Chan Lee. "Bankruptcy prediction using support vector machine with optimal choice of kernel function parameters." Expert systems with applications 28.4 (2005): 603-614.
[34] Mourao-Miranda, Janaina, et al. "Classifying brain states and determining the discriminating activation patterns: support vector machine on functional MRI data." NeuroImage 28.4 (2005): 980-995.
[35] Byvatov, Evgeny, et al. "Comparison of support vector machine and artificial neural network systems for drug/nondrug classification." Journal of Chemical Information and Computer Sciences 43.6 (2003): 1882-1889.
[36] MacNeal, Richard H., page i., "The NASTRAN Theoretical Manual", December 1972.
[37] "NASA Press Release 2008." http://www.nasa.gov/centers/dryden/news/XPress/stories/2008/10-08 technology.html. 2008.
[38] Jamshid Samarah and Sasan Armand. "Pressure Vessel Design Concepts for Planetary Probe Missios." 11th International Planetary Probe Workshop. Pasadena, CA. Jun 16-20, 2014.
[39] Jing Pei. "Analytical Look at Launch Vehicle Propellant Slosh Instability". Vehicle Analysis Branch Tech Talk. Presentation. Jun 12, 2014.
[40] Reyhanoglu, M. "Maneuvering control problems for a spacecraft with unactuated fuel sloshdynamics." Control Applications, 2003. Proc 2003 IEEE Conference. Volume 1, 23-25 June 2003, pp695-699.
[41] Veldman, A.E.P. et al. "The Numerical Simulation of Liquid Sloshing On-Board Spacecraft." J. Comp. Phys. 224 (2007) 82-99.
[42] "Falcon Demo Flight 2 Flight Review Update." SpaceX. June 15, 2007.
[43] Jing Pei, John Wall. Estimation of Aerodynamic Stability Derivatives for Space Launch System and Impact on Stability Margins. NASA/TM-2014-0002405. 2014.

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