Applied AI in Complex Systems: Examples and Lessons Learned

Da Ruan

The Belgian Nuclear Research Centre (SCK•CEN), Boeretang 200, 2400 Mol, Belgium
Email: druan@sckcen.be

Abstract

An overview on applied AI techniques in control and decision making for complex systems will be given mainly based on the 10 years progress of the FLINS forum (Fuzzy Logic and Intelligent Technology in Nuclear Science). After an outline of application areas of applied AI over the last four decades, the FLINS forum will be briefly introduced. Three concrete examples on nuclear reactor control, safeguards information management, and cost estimation under uncertainty for a large engineering project will be illustrated for the potential use of applied AI in complex systems. Recommendations and future research directions on applied AI in complex systems will be suggested from a practical point of view.

Keywords: Applied AI, soft computing, nuclear reactors, safeguards, information management, cost estimation, uncertainty.

1. Introduction

Applied AI, also known as advanced information-processing, has already enjoyed considerable success in complex systems. In recent years there has been a growing interest in the need for designing intelligent systems to address complex (nuclear) engineering problems. One of the most challenging issues for the intelligent system is to effectively handle real-world uncertainties that cannot be eliminated. These uncertainties include sensor imprecision, instrumentation and process noise and disturbances, unpredictable environmental factors, to name a few. These uncertainties result in a lack of the full and precise knowledge of the system including its state, dynamics, and interaction with the environment. Applied AI, based on soft computing techniques, including fuzzy logic, neural networks, genetic algorithms and others have shown great potential to solve these demanding, real-world problems that exist in uncertain and unpredictable environments. These technologies have formed the foundation for intelligent systems. To meet these research needs in nuclear systems, a forum for scientists and engineers working in computational intelligence has been formed which has proven to be instructive and vital (Ruan et al., 2005). Three real-examples from the FLINS projects will be examined through a SWOT analysis (strengths, weakness, opportunities, and threats): nuclear reactor control in Section 2, safeguards information management in Section 3, and cost estimation under uncertainty in Section 4. Essential steps on implementing AI in industry will be presented via R&D, demonstration, and commercialization. Challenges and future research directions will be concluded in this lecture.

2. Nuclear Reactor control

The need for on-line reactor operator support systems has become evident after the Three-Mile-Island (TMI) accident in 1979. Since then, considerable attention has been paid by the engineering, scientific, economical and political communities and society at large to prevent this type of events by using State-of-the-Art artificial intelligence techniques (Ruan and Fantoni, 2002). Among the techniques available today, the use of fuzzy logic control (FLC) as a means of expressing linguistic expressions mathematically, has been recently applied to nuclear reactor control.

2.1. Four Reactor Projects

One of the best-known research projects in this area is the successful application of FLC to the 5-MWt Massachusetts Institute of Technology (MIT) research reactor around the mid of 1980's (Bernard, 1988). A rule-based, digital, closed-loop controller that incorporates fuzzy logic has been designed and implemented for the control of power on the MIT research reactor. The advantage of rule-based systems is that they are generally more robust than their analytic counterparts in the above work. Therefore, the rule-based and analytic technologies should be used to complement each other, with rule-based systems being employed both as backups to analytic controllers and as a means of improving the man-machine interface by providing human operators with the rationale for automatic control action.

A fuzzy control system was also developed for a feedwater control system of the 165 MWe FUGEN Advanced Thermal Reactor (ATR) in Japan. A simulation study for this project was carried out from 1987 to 1988 and the development of a prototype system that had an on-line support function from 1989 to 1991. The practical fuzzy control system was introduced to the actual feedwater control system of FUGEN in July 1992. The operation of FLC system of FUGEN has successfully fulfilled its function during the validation tests. Fuzzy control was a small part of the whole system's implementation, but has enabled operators at FUGEN to more effectively control the steam drum water level while compared to a conventional PI control system in this particular circumstance (Iijima et al., 1995).

In an R&D project on fuzzy control to the BR1 (The Belgian Reactor 1) for controlling the power level of a nuclear reactor, the study was intended to assess the applicability of fuzzy control in this domain. The final goal was to develop an optimized and intrinsically safe controller. During the project, a fuzzy logic controller was proposed and first tested by comparing it with the classical controller of BR1. In the next step the BR1 reactor at SCK•CEN was used as a test bed to implement a PLC-based hardware controller. The BR1 reactor is internationally regarded as a nuclear calibration reference. It therefore provides an excellent environment for this type of experiments, because over the years considerable knowledge of the static and dynamic properties of the reactor has been accumulated.

The project (1995-1999) aimed at investigating the added value and technical limits of fuzzy control for nuclear reactor operations. The progress made in these experiments including closed-loop experiments has been published (Ruan, 2002). By July 1998, a permission to carry on the closed-loop test at BR1 under fuzzy control was obtained. The very first closed-loop experiment was successfully carried out in September 1998. It should be noted that this experiment and later closed-loop experiments were only on the steady-state operation. The project as a feasibility study on fuzzy control to nuclear reactors fulfils its function.

Although the experiments showed good results in approximating the classical controller, they are still not yet complete. To really prove the correct behavior of FLC in the steady-state operation, it is absolutely necessary to do closed-loop testing. It is therefore important to get the necessary licenses from the safety authority, which will allow us in the future to perform more closed-loop control experiments at BR1. The flexibility of FLC is demonstrated in the last fuzzy control closed-loop experiment (Ruan, 2002). It is shown finally that FLC can easily be extended to include new inputs and rules, and thus make it applicable in new control situations. The final controller is expected to be extremely robust against variations of external parameters, such as variation of the reactor core temperature (important during the start-up and shut-down of the reactor), cooling rate, and ageing of the fuel elements. This, however, needs further R&D efforts. Recently, a series of simulated experiments has been carried out using adaptive fuzzy control, ANNs and GAs to find out which strategies are most promising for further research and future application in nuclear reactor operation.

At ININ in Mexico another research project on controlling neutron power of a TRIGA Mark III research reactor with fuzzy control by a slightly different approach has been carried out. Over the past years, the study for this project was mainly devoted to the comparative study of different fuzzy control algorithms for a nuclear reactor with some extended simulation results (Benitez et al., 2004). The project has been partially supported by CONACYT. ININ has recently upgraded its TRIGA Mark III Reactor's control room to a digital system, which makes it much easier for further fuzzy control and other intelligent control algorithms/tools to be implemented as a test bed. The new research plan for this project is foreseen under the support of CONACYT.

2.2. Strengths, Weakness, Opportunities and Threats

All four projects have independently experimented with fuzzy control in their own reactors respectively and successfully demonstrated a feasibility of using an FLC in their reactors as a test bed in different degrees. These principal investigators of each of the four projects are currently all available. Excellent research platforms (such as BR1 and TRIGA) for conducting complex systems as a test bed are also available. Research on this topic (at least for BR1 and TRIGA) remains dynamic and challenging. International cooperation on this topic (as an example of ININ and SCK•CEN) is foreseen.

Limited man-power resulted in a small-size and limited-funds project. It is understandable that such fuzzy control for nuclear reactors will not generate any extra income as those in the realms of consumer products, intelligent control (non-nuclear systems), and industrial systems. Moreover due to the safety regulation, new implementation of any type of new technology including fuzzy control would take a much longer time for a license. This is only for some hardware part of nuclear technological implementation. Lack of sufficient cooperation (even for the same institute) between operators, engineers, and computer/AI specialists is a crucial drawback of such projects.

The nuclear power industry is enjoying a renaissance as evident by a number of new developments over the last five years. These new developments include: (1) announcement by nearly all nuclear power plants in the United States to implement 20 year life extension; (2) life extension already granted by the U.S. Nuclear Regulatory Commission (NRC) to a number of nuclear power plants for an additional 20 years of operation beyond their current 40 year license; (3) a strong desire to reduce dependence on oil imports; (4) increased interest in the role of the nuclear energy in protecting the environment; (5) improved efficiency and safety of current generation of plants; (6) success of advanced reactor designs; (7) progress toward disposal of high-level nuclear waste; and (8) improved legislative environment for increase use of nuclear energy (Hashemian, 2002).

The above items (2) and (5) etc. are direct implications for the opportunities of fuzzy control projects for nuclear reactors. All fuzzy control applications to nuclear reactors are targeted with such items as the mission and objectives of such projects described in Section 2. The preliminary research results (Ruan, 2002) confirm such opportunities for the safe and economic operation for nuclear reactors for many years to come. Activities related to fuzzy control in nuclear systems are still on the individual basis with a very small group (like the four projects outlined in this paper). For most existing nuclear reactors in the world, control techniques are relatively simple and old fashioned. This is perhaps enough for the current operation of nuclear reactors in the limited years to come. However, for a long run of those nuclear reactors, especially with the fast developing information technology today, such simple and old fashioned techniques will have to be upgraded in one or another way. Newly AI based intelligent control, including fuzzy control and a possible combination of traditional PID and new AI control, will play an important role as complementary to traditional methods both for enhancing safety level and economic operation of the reactors. To carry on such fuzzy control to nuclear reactors for extending the current use of the reactors as well as for designing the future possible new reactors, the need in term of sufficient multi-disciplinary efforts and certain priority as R&D strategies is evident. Otherwise, such research will not lead to valuable developments neither for any further demonstrations and implementations in a real nuclear power plant.

3. Safeguards Information Management

Assurance of non-diversion of nuclear materials is the ultimate goal of safeguards. Many countries, concluding comprehensive safeguards agreements (INFCIRC/153 type) with the International Atomic Energy Agency (IAEA), are currently discussing the new additional protocol (INFCIRC/540). The protocol will make them provide more information to the IAEA. Compared to the traditional regime, additional measures are taken into consideration in this strengthened safeguards regime. The new measures will essentially consist in having access to more information that can be very qualitative in nature.

The information collected by the IAEA comes from mainly three different sources: information provided by the State, information collected by the IAEA, and information obtained from open sources (like media, studies, provided by third parties, etc.). It is obvious that the amount of data is enormous and that not all information contributes to a better knowledge of the situation in a particular State. This information can be of very different nature: it can be relevant, or it can be uncertain, like fuzzy or vague (due to the imprecise boundary), incomplete (due to lack of information), abundant (due to the limited ability of human beings to perceive and process simultaneously large amounts of data), conflicting (due to different sources), fragmentary (the information usually related to a fragment of the problem, and different fragments can be covered by various information sources), not fully reliable (due to different sources for different purposes), and deficient. This information does not directly contribute to a better knowledge of the facts, nor does it facilitate decision-making.

The final conclusion on the non-proliferation commitment and on the absence of any undeclared activities of a State has to result from the balancing of all information in an integrated way. The IAEA has to process and evaluate a large amount of data, which is available from the different sources as described above.

Hence, there is an important need to establish a mathematical framework that provides a basis for synthesis across multidimensional information of varying quality, and provides an evaluation method that enables the IAEA to derive a final estimation on the possibility degree that “No nuclear material in a certain country is used for manufacturing nuclear weapons.”

Traditional study of such issues is conducted using probabilistic tools and techniques. However, it is not difficult to see that aspects related to imprecision or vagueness clearly have a non-probabilistic character since they are related to imprecision of meanings.

Usually, in a quantitative setting the information is expressed by means of numerical values. However, when we work in a qualitative setting, that is, with vague or imprecise knowledge, this cannot be estimated with an exact numerical value. Then, a more realistic approach may be to use linguistic assessments instead of numerical values, that is, to suppose that the variables that participate in the problem are assessed by means of linguistic terms.

A flexible and realistic linguistic assessment approach is developed to provide a mathematical tool for synthesis and evaluation analysis of nuclear safeguards indicator information. This symbolic approach, which acts by the direct computation on linguistic terms, is established based on fuzzy set theory. More specifically, a lattice-valued linguistic algebra model, which is based on a logical algebraic structure of the lattice implication algebra, is applied to represent imprecise information and to deal with both comparable and incomparable linguistic terms (i.e., non-ordered linguistic values). Within this framework, some weighted aggregation functions introduced by Yager (1993, 1998) are analyzed and extended to treat these kinds of lattice-value linguistic information. The application of these linguistic aggregation operators for managing nuclear safeguards indicator information is successfully demonstrated (Ruan et al., 2003).

4. Cost Estimation under Uncertainty for MYRRHA

MYRRHA is an Accelerator Driven System (ADS) under development at the Belgian Nuclear Research Centre (SCK•CEN). It aims to serve as a basis for the European experimental ADS to provide protons and neutrons for various R&D applications. The project started in 1997. After a conceptual period of two years, a pre-design phase has been launched and is to be completed by 2006. After a detailed engineering design phase and construction of the components, MYRRHA will be put in service around 2015.

The possible cost for MYRRHA at this stage might include: (1) the MYRRHA machine and its related materials, (2) R&D activities, (3) Feasibility and pre-design studies, and (4) licensing. Just for the item (1), all possible expenses are far from detailed and the expenses are those that would be incurred after the decision to construct the MYRRHA machine (around 2008). This means that all problem areas (spallation source, problems related to the accelerator, LBE connected problems, robotics, fuel, and instrumentation) are given a reasonable satisfactory solution and that the pre-design has come to a point that no technical major problems are to be expected any more.

There are many ways to assess a machine cost. Classically, the costs of the above-mentioned item (1) are separated in a coarse way into: (1) material cost, (2) engineering cost (manpower & overhead cost, profit, …), (3) manufacturing costs (manpower & machinery investment & overhead cost, profit, …), and (4) others. It is not always clear when this distinction is to be made and this separation can be used in a more arbitrary way to facilitate the cost estimation of a particular item. E.g., the reactor vessel is not a complex component and one can (more or less) easily estimate its cost by adding the material, the engineering and the manufacturing costs and if necessary some other not specified costs. On the other hand some components (e.g., bearings, motors, drives, …) are industrially available and for those components the cost separation is useless. In those cases, only the expected purchase price is considered as "other costs." However, it's very difficult to estimate the price all at once as we are just in the pre-design phase without any detailed technical drawing of any part of the machine. So, all estimations are more or less rough guess under various uncertainties. Especially estimating the input parameters may be difficult at early stages of the design due to lack of data or insight. In addition, historic data for construction are very much limited and more importantly are unreliable. To overcome data difficulties, a probabilistic technique, usually the Monte Carlo simulation (MCS) may be employed, where it is required to determine a probability distribution function (PDF) for every uncertain variable to carry out an MCS. Such functions are best derived from statistical analysis of significant data. But, as mentioned previously, historic data are sparse; therefore it is questionable whether statistically meaningful PDFs can be derived.

Thanks to the Intelligent Decision System (IDS) (Yang et al. 2001), a software package designed to assist multi-attribute decision analysis or multi-criteria decision-making under uncertainties by The University of Manchester, a better cost estimation for the MYRRHA machine is being carried out on the cooperation between SCK•CEN and The University of Manchester.

As a case study for modeling cost estimation for the MYRRHA project using IDS, we only consider item (1) the MYRRHA machine and its related materials, and do not include the costs for: (2) R&D activities; (3) Feasibility and pre-design studies, and (4) Licensing. In IDS, many dialog windows are designed to support model building, data input, result analysis, reporting and sensitivity analysis.

IDS can accept input data (cost estimate for each decomposed item in the hierarchy) with or without uncertainties: quoted costs from suppliers, rough guess with a range, and cost estimate from a group of experts whose estimates may not agree with each other, cost estimates with probabilistic uncertainty or subjective uncertainty. In summary, this approach involved in IDS has the following main features in cost analysis: (1) there is no need to convert probability distributions into average numbers; (2) uncertain or incomplete information can be used - maximum use of available information; (3) it can also be used for benefit analysis and cost-benefit trade off analysis. And the main benefits would be: (a) provide a structured, flexible and natural framework for analyzing complex cost estimation problems; (b) support more consistent, reliable and informative cost estimations and comparisons between different options; and (c) facilitate more effective and efficient knowledge management and communication (Yang, 1994).

5. Conclusion

In this talk, the first example of the four nuclear reactors only reflects a very small part of R&D efforts in the framework of intelligent control in safety systems. The second example on safeguards information management would be more interesting for development of reliable intelligent systems for safety-related issues such as security, anti-terrorist, etc. However, the current project will need more R&D efforts. The last example of cost estimation under uncertainty is a common issue for large scale engineering projects. Intelligent systems, decision support tools, and applied AI techniques are most suitable for such applications.

6. References

[1] J.S. Benitez-Read et al., "Properties of continuous and discrete methods for the aggregation and the COG stages in the power control of a TRIGA reactor, in: "*Applied Computational Intelligence*," 603-603, 2004.

[2] J.A. Bernard, "Use of a rule-based system for process control," *IEEE Control System. Mag*. 8 (5), 3-13, 1988.

[3] H.M. Hashemian, "Optimized maintenance and management of ageing of critical equipment in nuclear power plants," in: [7], 41-49, 2002.

[4] T. Iijima et al., "Application of fuzzy logic control systems for reactor feedwater control," *Fuzzy Sets and Systems* 74 (1), 61-72, 1995.

[5] D. Ruan, "Initial experiments on fuzzy control for nuclear reactor operations at the Belgian Reactor 1," *Nuclear Technology* 143, 223-240, 2002.

[6] D. Ruan, J.W. Hines, and I. Pazsit, "Computational intelligence in nuclear applications: lessons learned and recently developments," Special Issue of *Progress in Nuclear Energy*, in press (2005).

[7] D. Ruan and P.F. Fantoni (Eds.), "*Power Plant Surveillance and Diagnostics*," Springer, Heidelberg, 2000.

[8] D. Ruan, J. Liu, and R. Carchon, "Linguistic assessment approach for managing nuclear safeguards indicator information," *Int. J. of Logistics Information Management* 16 (6), 401-419, 2003.

[9] R.R. Yager, "An approach to ordinal decision making," *Int. Journal of Approximate Reasoning* 12, 237-261, 1993.

[10] R.R. Yager, "Fusion of ordinal information using weighted median aggregation," *Int. Journal of Approximate Reasoning* 18, 35-52, 1998.

[11] J.B. Yang and M.G. Singh, "An evidential reasoning approach for multiple attribute decision making with uncertainty," *IEEE Transactions on Systems, Man, and Cybernetics* 24, 1-18, 1994.

[12] J.B. Yang, J. Wang, D.L. Xu, B.G. Dale, O. Kieran, and T. Ruxton, "Multiple criteria decision analysis applied to safety and cost synthesis," *Journal of UK Safety and Reliability Society*, 21 (2), 42-63, 2001.