CONF-851102--117

UCRL--93612

DE87 008738

AUTOMATION OF NEUTRAL BEAM SOURCE CONDITIONING WITH ARTIFICIAL INTELLIGENCE TECHNIQUES

R. R. Johnson
T. W. Canales
D. L. Lager

This paper was prepared for submittal to

11th Symposium Fusion Engineering
Austin, Texas

November 18-22, 1985

Lawrence Livermore National Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

AUTOMATION OF NEUTRAL BEAM SOURCE CONDITIONING WITH ARTIFICIAL INTELLIGENCE TECHNIQUES

Rowland R Johnson, Tom Canales and Darrel Lager
Lawrence Livermore National Laboratories
P.O. Box 808
Livermore, California 94550

Abstract: This paper describes a system that automates neutral beam source conditioning. The system achieves this with artificial intelligence techniques. The architecture of the system is presented followed by a description of its performance.

Introduction and Motivation

Magnetic Fusion Energy experiments are done with systems that are composed of several complex subsystems. It is clear that in order for MFE to be feasible that *most, if not all, of the subsystems must be* operated automatically. The goal of this project is the automation of one of these subsystems.

A major concern of all MFE experiments is plasma generation which is accomplished with a device called a neutral beam source. A source first ionizes a gas and then sends it through an accelerator to impart energy to it. A newly manufactured source cannot operate reliably at a power level required to support fusion. The source must be started at low power levels and slowly brought up to the higher power levels. This process, known as conditioning, is also required when a source is overhauled. Conditioning and the day to day operation of a source are done under the supervision of a operations staff.

Source conditioning may be viewed as a conventional control system with the operator being the controller. However, a conventional control system theory approach is unworkable since it relies, in part, on being able to model the conditioning process in a precise way. The operator decides on parameters and sends them to the source. The source runs for a short time in which measurements are taken and sent to the operator. *The combination of input parameters and* output measurements are known as a shot. After several good shots at one power level the source becomes "conditioned" enough to run at that level. *Under certain conditions an operator will then try to* raise the power level for the next shot. If good shots are obtained then that power level is maintained. If not, the power level must be reduced or "deconditioning" will happen. Conditioning then is just a sequence of shots with the ultimate goal of running at high power levels.

Using expert system techniques for automatic conditioning is a viable alternative since operators do quite well at the task of conditioning. The purpose of an expert system is to provide the expertise that has been acquired by an operator through experience. No attempt is made to analyze this experience and arrive at a theory that explains it. Rather, the goal is to codify the manner in which an operator represents knowledge and reasons about the process.

The overall configuration used for conditioning is shown in Fig. 1. Normally, the operator receives data from the standard display, determines shot parameters for the next shot and sends them to the database. When the expert system is being used it gets the same data provided by the standard display and derives shot parameters for the next shot. The operator reviews the suggestions made by the system and, if appropriate, uses them.

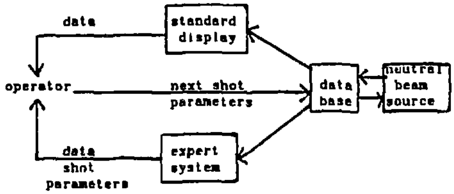

Figure 1.

Ultimately, the operator will be removed from the loop and be called upon only in rare situations. Presently, this configuration provides an effective means to extract the necessary information from the operator and encode it in the expert system. In addition, it insures that an error made by the expert system will not go unchecked and cause serious damage to the source.

Expert System Techniques

This system uses a forward chaining rule based inferencing technique. Essentially, the knowledge of an operator is encoded in a set of rules. The idea of a rule is much like that of an IF-THEN statement in a programming language. Rules have the form

```
(RULE <rule-name>
      <condition>
      <action>)
```

and means that when <condition> is true the <action> is executed. Currently, there are well over 300 such rules in the system. Basically, the system iterates on the following two steps. First, it finds a rule with a true <condition>. Second, this rules <action> is executed which may cause more rules to have a true <condition>. This iteration continues until all the rules with a true <condition> have had their <action> executed.

Knowledge engineering is the process of developing a set of rules that encode an operator's knowledge. *Although the concept of a rule is straight* forward, knowledge engineering is a difficult task. The difficulties arise when large numbers of interacting rules are used. Discussions with operators result in new rules being added. Often, old rules that used to work now do not work as a result of the new additions. As the number of rules grow it gets more difficult to add new rules.

The system provides a programming environment that facilitates rule development. The primitives that make up <condition>s and <actions>s are meant to reflect the operators representation of the problem. Old rules are easily changed and new rules are just as easily added. In short, the task of knowledge engineering is not hindered by the task of knowledge encoding.

One requirement is that the results of several past shots must be examined by the rules. This history mechanism is implemented by placing each piece of information about a shot is contained in a named register. *A shot register set is all of the registers containing information about a particular shot* The system uses the shot register sets. SHOT-N, SHOT-(N-1), ... ,*SHOT-1, SHOT-0* and *SHOT+1*. *SHOT-0 is the* most recently completed shot and SHOT+1 is the next shot to be fired. SHOT-1, SHOT-2,...,SHOT-N are the shots occurring before the most recent shot.

When a shot is fired each shot register set SHOT-i becomes *SHOT-(i+1), e.g. SHOT+1 becomes SHOT-0*, SHOT-0 becomes SHOT-1 ,etc. SHOT-N is discarded and a new shot register set is created that becomes SHOT+1.

The value of a register is obtained with the form

(<shot register set> <register name>)

For example.

(SHOT-3 Avg-Vaccel)

yields the average value of Vaccel in SHOT-3. The form

(SETR <register name> <value>)

sets <register name> to be <value> in SHOT-0. This is used primarily in analyzing the most recent shot. *Similarly, the form*

(SETR-NEXT <register name> <value>)

sets a register in SHOT+1. The primary use being to assign suggested shot parameters. Registers in SHOT-n through SHOT-1 were set when they were SHOT-0 or SHOT+1.

Controlling the Source

It was determined that source conditioning requires that two processes be controlled. The primary goal of the system is to control the conditioning process through the use of expert system techniques. In order to accomplish this it is necessary to control the accelerator process. Furthermore, the accelerator process can be controlled with conventional control system techniques. *This observation resulted in a* system that is a hybrid of expert and control system techniques.

Specifically, the operator controls the conditioning process by choosing Vaccel and Delta-Iaccel. Delta-Iaccel is actually a range of values that represents how far off density the value of Iaccel should be. For example, Delta-Iaccel = [-1.5,-.5] means that Iaccel should be .5 to 1.5 amps underdense. The value of Parc must be derived from the Vaccel and Delta-Iaccel in order to control the accelerator process.

In order to achieve this type of control the work done by [1] was used. This approach uses the Child-Langmuir law

$$IaccelD = P * Vaccel^{e} \qquad (1)$$

and the formula

$$Parc = f * IaccelA + g \qquad (2)$$

IaccelD is the value of Iaccel required for the source to operate on density for the given Vaccel. It should be noted that e is not equal to 1.5. The actual value of e varies with the source and was observed to be in the interval [1.67,1.71]. Efforts to resolve this discrepancy have been *unsuccessful*.

Formula (2) represents a model of the accelerator where *IaccelA is the actual value of Iaccel for the* given Parc. A Kalman filter is used as a parameter estimator to determine the constants f and g. The expert system determines when it is appropriate to run the parameter estimator. It also uses the errors encountered by the parameter estimator as a source *diagnostic*.

Once Vaccel and Delta-Iaccel have been determined (1) and (2) are used to determine a range of Parc that is acceptable. If the current value of Parc falls in this range then it is used. Otherwise, the lower value of the Parc range is used.

Rule Organization

For each shot the system evaluates, in sequence, four separate groups of rules. Each such evaluation is called a phase and accomplishes a specific task. The four phases are signal processing, analysis, set-parameters, and display. Depending on the shot, the signal processing phase executes the appropriate signal processing routines. The display phase determines what waveforms the operator should see. Following are a detailed discussion of the analysis and set-parameter phases.

One objective of the analysis phase is to derive a high level description of the shot. To this end a descriptive set of registers are used. The registers shots-since-last-increase, shots-since-last-decrease, and shots-since-last-change describe the current state of Vaccel. The mode register contains 'ADVANCING if the current strategy is to try to increase Vaccel and 'RETREATING otherwise. The territory register describes where Vaccel in relationship to where the source is conditioned. 'OLD means that Vaccel is below where the source is known to be conditioned. 'NEW represents that Vaccel is equal or greater than the conditioned level. Finally, 'BRAND-NEW means that Vaccel is at a point where significant accelerator on-time has not been obtained.

An attempt is made to describe the shot in several other ways as well. Consider the rule

```
(rule short-term-trend
      (and (shot-0 %-on)
           (shot-1 %-on))
      (setr short-term-trend (/ (shot-0 %-on)
                                (shot-1 %-on))))
```

The <condition> for this rule is true if the percentage on-time for this and the last shot have been computed. If so, the <action> is executed and sets a register called short-term-trend that is the ratio of these two percentages. This register is used in the set-parameters phase to determine if conditioning is beginning to happen.

The analysis phase also runs the Kalman filters if there was sufficient on-time to assure accurate results. The differences between the expected and actual measurements are analyzed. Since the models appear to be incomplete the large differences that are expected in certain situations are ignored. A large unexplained error is indicative of possible source problems and the operator is informed.

The source has an elaborate mechanism for detecting, handling, and reporting faults. The reported faults are checked for consistency with each other and with other data. Inconsistencies imply source problems and are reported.

Finally, a search is made of all waveforms for any unexplained high frequency energy. Such an occurrence is often symptomatic of problems that, if allowed to persist, may lead to source damage.

The set-parameters phase uses the information produced by the signal processing and analysis phases to determine the suggested parameters for the next shot. For example, consider the rule

```
(rule set-vaccel-suggested-110
    (and (equal (shot-0 territory) 'old)
         (equal (shot-0 mode) 'advancing)
         (>= (shot-0 shots-since-last-change) 3)
         (< (shot-0 short-term-trend) 1.2)
         (< (max (shot-0 max-duration)
                 (shot-1 max-duration)
                 (shot-2 max-duration))
            100.0))
     (prog()
        (setr-next v-accel-setpt-suggested
                   (1- (shot-0 v-accel-setpt)))
        (setr-next min-delta-iaccel-suggested -2.0)
        (setr-next max-delta-iaccel-suggested -1.0)))
```

This rule looks for situation where the source is being operated in old territory, i.e. it has been conditioned at this level. The current strategy is to advance Vaccel when possible. The last change was to increase power but the last 3 shots have been the same. During these last 3 shots the maximum contiguous on-time has been less than 100 milliseconds. Finally, there has been no improvement in the short term. The action of this rule is to suggest that Vaccel be reduced by 1. In additioned the desired value of Iaccel is 1 to 2 amps under the value required for operating on perveance. This reflects the operator's desire to run slightly underdense when changing levels.

Operator Interface

The system's operator interface consists of a single 19" monochrome display. It is subdivided into 11 windows. Nine of these are to display waveforms; one is used to give commands to the system. Finally, the last is the log window. An example of the log window appears in Fig. 2. The top half is a log of the last 5 shots. It contains averages for selected waveforms in addition to arc chamber plasma uniformity (A:B), number of accelerator interrupts, and beam duration. The box labeled SET POINTS NEXT SHOT contains the system's suggestions for Vaccel and Parc on the next shot. In this case the system suggests that Vaccel be increased to 63 Kv and Parc be increased to 58.5 Kw. To the left of this is information about the system's suggestions versus the actual operator input for the most recent shot. To the left of this are the faults detected by the source.

The lower left portion of the log window contains four mouse selectable functions. The mouse cursor is moved over the desired box and a mouse button is pressed to obtain the desired function. PLOTS MENU brings up a window that allows the operator to display any configuration of waveform displays. SET PLOTS causes the current configuration of waveform displays to become permanent. EXPLAIN brings up a window containing an explanation of the system's reasoning in determining the next shot suggestions. This is particularly useful in the knowledge engineering process. The ANOMALIES box flashes when there are conditions that require operator attention. These conditions are displayed in a window when this function is selected.

Performance

Measuring the performance of the system is difficult because conditioning is a non-repeatable process. Therefore, it is not possible to condition the same source with an operator and then with the expert system. Since it is not possible to determine performance on a comparative basis two other metrics were used to determine performance.

The first is a "measure of does it successfully condition a source". The disadvantage of this metric is that testing time was limited and it was not possible to use the system for the entire range on any one source. However, the system was used several times in the 55-75 Kv range and successful conditioning was achieved.

The second is a "measure of does it make the same decisions that an operator makes". It is important to note that individual operators vary with each other and, at times, with themselves. Nonetheless, an attempt was made to determine the operator's judgement of the quality of each suggestion made by the system. These judgements fall into four categories. Most were in the first category where the suggestions were judged to be the same as an operator. Some fell into the second category in which the system's suggestion was judged to be better than the operators. This occurred mostly because the system's methods of com-

Shot-#	Vaccel	Iaccel	Parc	Iarc	Varc	Igg	Isupp	A:B	Ints	Duration
4280.0	61.251	56.977	59253.0	1508.4	39.236	26.793	6.9111	1.0802	4.0	466.48
4279.0	60.08	57.122	59929.0	1515.4	39.498	-22.223	6.872	1.1311	5.0	445.36
4278.0	60.14	54.408	56826.0	1450.3	39.133	-33.573	6.2875	1.1347	4.0	450.36
4277.0	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	20.0	3.892
4276.0	NIL	NIL	NIL	NIL	NIL	NIL	NIL	NIL	20.0	1.112

PLOTS MENU
SET PLOTS
EXPLAIN
ANOMALIES

ARC RATIO DETECTED
ARC CROWBAR
TERMINATE SHOT
SPOT DETECTED

Setpoints actual/sugg
V accel Kv: 61.0/NIL
Density %: 97.0/NIL
P arc Kw: 57.0/NIL
Iaccel: -2.0126762

SET POINTS NEXT SHOT
V-accel 63.0 Kv
Density NIL %
P-arc 58.5 Kw

INTERRUPTS: IN DI 4 GG 0 SCR 0 I accel 0 SUPPR 0 D-DOT 0

Figure 2.

puting averages, on time, etc are more precise than that of the operators. The third category were suggestions that operators felt were incorrect. However, the number of such suggestions was not large enough to prevent conditioning. Finally, in the fourth category are the catastrophic suggestions in the sense that, if followed, damage would be done to the source. There were none in this category.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Labs under contract number W-7405-ENG-48.

The authors are indebted to Bob Pancotti, Gary Preckshot, and John Woodruff for the help received in implementing the system. Bob Wyman conceived the concept of building the system and supported it. Bill Labiak, Ken Autio, Ken Gillespie, and Jim Sullivan provided the operator expertise through many, many hours of conversation.

References

[1] E. Thiel, "Simulation of Automatic Control of MFTF-B Neutral Beams," Lawrence Berkeley Labs Report LBL-19252

[2] G. Pollock, "Automation of Multiple Neutral Beam Injector Controls at Lawrence Livermore Laboratory," 7th Symposium on Engineering Problems of Fusion Technology, 1977