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Development of a Fuzzy Knowledge-Based System for the Control of a Refuse Incineration Plant

- Application of Advanced Fuzzy Techniques for a Complex Multivariable Control Problem

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Abstract:

A refuse incineration plant is a complex process, whose multi-variable control problems can not be solved conventionally by deriving an exact mathematical model of the process. The usage of advanced fuzzy technologies within the suitable development methodology is demonstrated by a controller implemented for the refuse incineration plant in Hamburg-Stapelfeld, Germany.

1. Refuse Incineration

Because of the heterogeneous composition of household refuses, most incineration plants were partly manually controlled by observing the combustion chamber by a human operator. Figure 1 shows the diagrammatic layout of a refuse incineration plant.

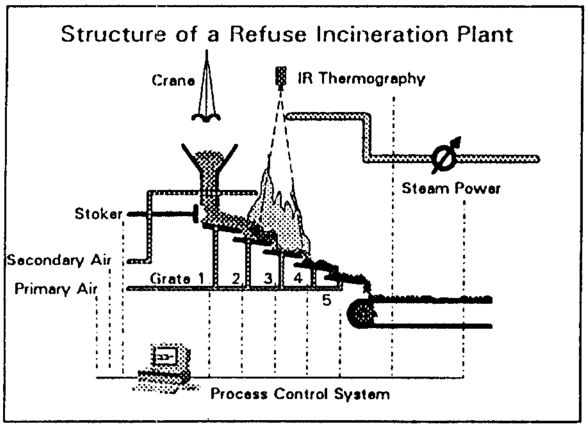

Figure 1: Schematic Structure of the Refuse Incineration Plant in Hamburg Stapelfeld

The incoming refuse is initially stored in a bunker and then transported by a gapple crane into the the feed hopper of the incineration plant. The refuse lands on the grate via the downshaft and feeder. The grate consists of two parallel tracks each with five undergrate air zones. The optimum position of the fire is in the middle of the third grate zone, since at this point the refuse is adequately predried and thereafter there is still enough residence time in order to ensure complete burnout.

Although the crane operator attemps to homogenize the refuse by mixing, it is not possible to maintain a uniform feed quality. The existing automatic systems and control circuits have as their main objective the maintainance of a constant thermal output with good burnout, thereby creating the preconditions for an uniformly high energy production. In order to attain this objective the plant operators must be highly qualified. In spite of such measures, in the majority of incineration plants it is not possible to dispense with manual intervention because of the extremly inhomogeneous composition of household refuse. During the course of manual intervention the operator observes the furnace and adjusts the refuse feed and the grate operating mode accordingly.

While the quantities of refuse to be incinerated are steadily increasing the enviromental laws are becoming ever more restrictive. Recent insights on the toxicity of chlorinated organic pollutant emissions have also dictated a change in the objectives of refuse incineration; together with the ideal of constant combustion output it is becoming ever more urgent to optimize the process in ecological terms, i. e. to ensure the largest possible reduction in volulme while minimizing emissions.
During combustion a control system must therefore maintain the following conditions:

- Control of the O2 concentration in the flue gas to keep it at a constant figure.
- Maintanance of a uniform thermal output.
- Maintanance of optimum flow conditions in the furnace and the first boiler pass with as little variation as possible so that the desired conditions for attaining the lowest possible degree of emissions

and thus preventing corrosion are always maintained (14).

These conditions can only be fulfilled by optimized combustion at a stable operation point. Conventional control systems are incapable of reacting to the inevitable local and intermittand inhomogeneities of the refuse fed to the grate, which are attributable to varying calorific values and ignition properties. It is as a result impossible to avoid pronounced variations in the combustion process and such variations are always associated with unfavourable emission figures.

The most important control variable at the plant is the steaming capacity. This is mainly affected by the primary air admitted to the various undergrate air compartements. Disturbances here occur as a result of the inhomogeneous composition at localized points. The primary air distribution must therefore be continually matched to the requirements of the individual grate zones. Since O2 content in the flue gas must be maintained at a constant figure the secondary and primary air are controlled in counterbalance to each other.

Between the feeder and the combustion zone there is always a quantitiy of uncombusted refuse whose amount varies in accordance with the feed quality. As a result of this storage effect there is no direct connection between feeder movement and the position of the fire on the grate. The position can only be registered by visual observation by the plant operators or video picture evaluation.

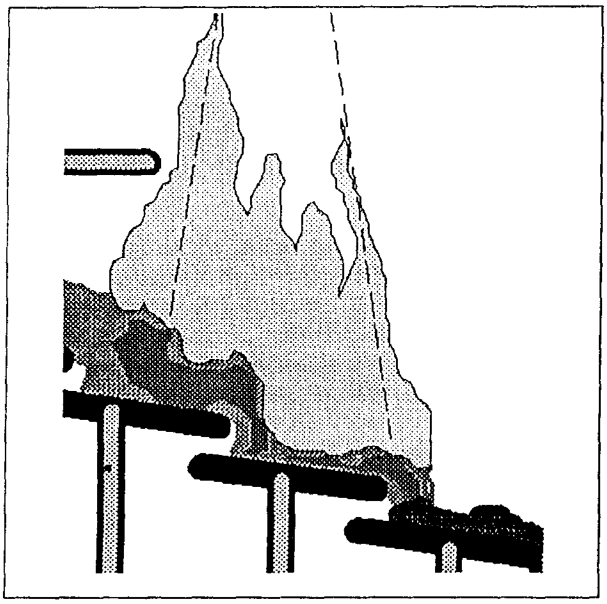

Figure 2: Covered observation area of the IR-camera

A possible method of automating this process is the registration of combustion by infrared thermography. This offers the immediate advantage that the plant operator is in a position to observe combustion directly from the control room. Because of the geometry of the furnace in the plant under consideration the area which must be observed lies mainly in grate zone 3, but also to some extent in zones 2 and 4, which cannot be so completely observed (Fig.: 2)

This is however more than adequate in order to determine the position of the fire. Additionally it is possible, by statisticall evaluation of the infrared picture, to determine the width of the combustion zone and derive from this information on asymmetric positions of the fire or secondary combustion zones.

Even if all the information given above is available it is still necessary to development an adequate mathematical model which will allow the information the information to be applied to a conventional control system. However combustion processes as a rule are of a highly non-linear nature and represent multi-variant problems. For conventional control system strategies the only feasable method is therefore to influence controllers by heuristic programming.

New solutions to problems of that kind are offered by the use of advanced control techniques. In particular fuzzy logic control has been applied to similar combustion processes [7,13]. Complex interactions between the various items of information evaluated require a methodology of structured information analysis.

2. Methods for the Development of Control Systems

Conventional technologies of process automization require a lot human resources: Beside the set-up of hardware and interfaces, operator's control knowledge must be acquired as well as control engineer's experience, and software specialists have to be called for the implementation. This presupposes, that all these specialists communicate with each other searching for a way to translate the control strategy into the code of a programming language. For this, human ideas, concepts and causalities often must be expressed on a technical level. Typically concepts are then described as functions and causalities represented as if-then-rules. As described [5,16,17,18], fuzzy logic, using linguistic variables with membership functions in if-then-rules, is an approved methodology to implement that kind of linguistic knowledge.

State-of-the-art in fuzzy logic control applications is the simple calculus of "fuzzy-if-then-rules" which predominantly use MIN/MAX. operators. While fuzzy control algorithm using this simple calculations have successfully been applied in a variety of control problems, these approaches are only a rough approximation of the linguistic meaning they have to represent.

This can be prevented by using fuzzy operators representing linguistic conjunctions like "and" and "or" [6,8,14] and by considering rules themselves as "fuzzy". Different advanced inference procedures were proposed by Zadeh [16] known as the "compositional rule of inference", Kosko[11] using so-called Fuzzy Associative Maps (FAMs) and others [10,12,15]. These concepts allow a "degree of support" (also called "degree of plausibility") to be associated with any rule. Zadehs concept enables a very fine tuning of the rules but involves a large computational effort that forbids its usage in most real-time systems. In order to that, Koskos FAMs only require a small computational effort but only introduce a "weight" factor to each rule.[1]

For both computational efficiency and appropriateness, a combination of these methods was found: The degree to which every rule fires is determined by aggregating the degree to which the premise is fulfilled with its degree of support [3]. Of course, this operation can be computed using a fuzzy operator. Applying the product operator for this item, the degree of support can be interpreted as a "weight" for every rule. This method is rather simple to use: first, define degrees of support of only either zero or one. Second, for fine tuning, use values between 0 and 1.

For larger systems handling 50 fuzzy rules and more, rule based systems are no longer lucid and easy to comprehend, if rules are represented in a simple list. Additional structural features enabling for example the classification of rules in rule blocks [3,4] coming with appropriate rule representations must be used.

The choice of appropriate methods for the knowledge representation is due to the fact, that appropriate software tools for the development of control systems are available. Although fuzzy control systems are sometimes programmed in a conventional programming language, for complex application, it is necessary to use a tool which prevents repeated programming fuzzy methods like inference strategies or defuzzification methods [2].

For the definition of a fuzzy control strategy, a variety of software tools based on the concept of compiling/precompiling which already exist in the market can be used. Although this concept works well for the development of conventional software, it has several inherent drawbacks for the construction of fuzzy control systems.

This work investigates which advanced methods render the application of fuzzy control in complex problems possible and how fuzzy controllers may be built more efficiently. The results of this theoretical work has already been implemented in a professional fuzzy logic development system.

First one has to define an initial control strategy as a prototype. Containing the complete structure of the desired system, the prototype is representing all items of the control strategy. For the given process, the prototype was set-up with 18 linguistic variables used in 70 fuzzy rules, with 9 rule blocks.

The control strategy is compiled and linked to the process or its simulation for testing.

3. Improvement of the Control System

If at first the controller does not work perfectly -- which happens often -- the control strategy must be revised. For the revision, existing debuggers are clearly inappropriate since they either work on the compiled code or do not work in real-time. Additionally, when a fuzzy control strategy is being designed for a continuous process or its simulation, optimization is done by trying small definition changes and then analyzing the subsequent reaction of the control loop. To recompile the controller, and thereby interrupting the continuity of the process, a small change is always made, development time is increased considerably.

For these reasons, on-line-technology has to be used for further optimization. With this tool, a fuzzy logic control strategy can be graphically visualized while the fuzzy system is actually controlling the process in real-time. This enables the engineer to understand the dynamic behaviour of both the controller and the process.

In the optimization step, one often wants to try out little modifications to the rule strategy or the membership functions to subsequently increase system performance. If a code-generating approach such as a fuzzy-precompiler is used, whenever a change is done, the controller has to be put off-line and the controller to be recompiled. In addition to being very inefficient, this approach has got another drawback: a continuous process is always put back to manual control out of its operating point by the recompilation. Hence, the effect of the control strategy modification can no longer be visualized by the engineer. This makes efficient optimization next to impossible. The incineration plant is a perfect example for such an application.

Once the system is readily optimized, a precompiler or compiler can be used for a code-optimized implementation of the final system on the controller hardware

As visualized in figurre 3, the development approach for complex fuzzy logic control systems must cover the following steps [9]:

I. Design: definition:

- The system design contains the definitions of linguistic variables, fuzzy operators, the fuzzy rule base and the defuzzification method.
- This should be supported by graphical design tools.
- The step results in a first prototype of the controller.

II. Off-Line Optimization:

- To check the controller's static performance, one can either test the controller interactively by applying input values and analyzing the information flow in the system or one can simulate the controller's performance on pre-recorded process data or a mathematical model of the plant, if available.

- For all debugging, simulation and analysing steps, a software implementation of the controller is necessary. Graphical analysing tools and debug features connected to graphical design tool ease the error detection and optimization.
- This step ends with a refined prototype.

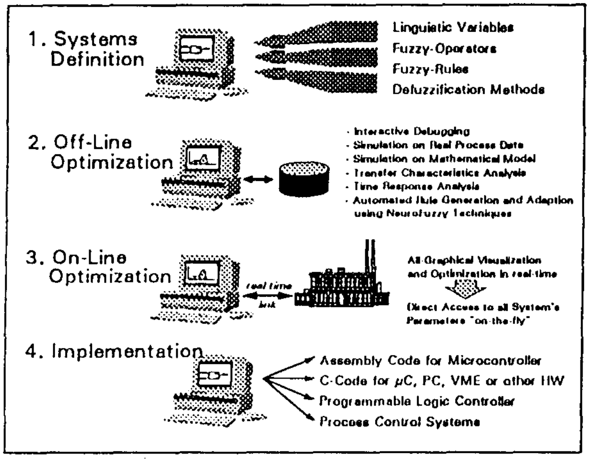

Figure 3: Development Methodology for Fuzzy-Logic Based Systems

III. On-Line Optimization:

- The refined prototype is now optimized on the running process.
- To allow for on-line development, the workstation/PC running the development tool must be connected to the process controller hardware by just a serial cable.
- This step establishes the final optimized system ready for implementation.

IV. Implementation:

- The optimized system is code-optimized for the final system.
- Highly optimizing precompiler and compiler specialized for the applied hardware can be used.
- Result is a controller software, code-size and runtime optimized.

4. A new Structure for the Control System

The application of advanced fuzzy logic development techniques has led to a new structure for the desired control system.

The system is devided into three stages in each of which a short-term and a long-term strategy is operated.

The first stage corresponds to a steaming capacity control circuit, subdivided into

- a short-term control cycle for the steaming capacity and
- a long-term control cycle influencing the O2 concentration in the flue gas.

The set value for the long-term control system is calculated from a combination of the O2 content together with the information obtained from the short-term control system on system behaviour.

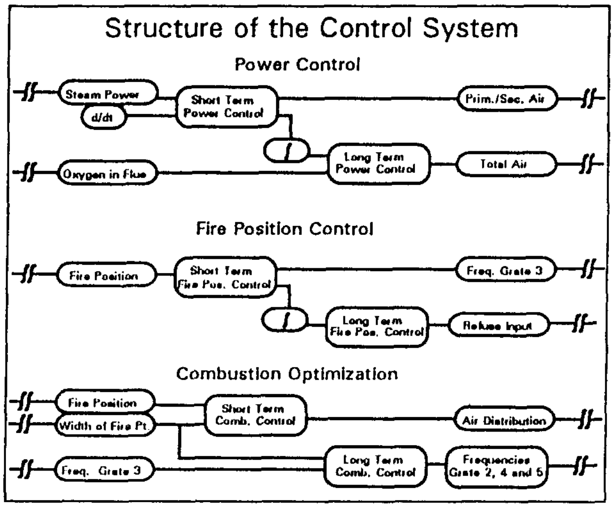

Figure 4: Structure of Fuzzy Control System

The second stage controls the throughput of refuse and here

- The grate movement is responsible for the short-term control of the position of the fire on the grate and
- The feeder is utilized for the long-term adjustment of the amount of refuse fed to the grate

Characteristic parameters from the IR thermography are utilized to determine the position of the fire on the grate at any given time.

The third stage, which serves to optimize combustion, additional information from IR-thermography is employed.. The optimization consists of the following steps:

- Control of the primary air for the various undergrate air zones.
- Control of the length of the fire by governing the feed velocity in the individual grate zones.

The utilization of fuzzy logic permits the integration of many disparate items of information. Besides directly measurable parameters such as, for example, the steaming capacity, various identifying parameters for the position of the fire and its lenghtare utilized which can be obtained from the IR thermography data.

The result is a hybrid system in which conventional calculation mthods are combined with the methods of fuzzy logic. This permits the uncertainties which ineevitably occur to be taken into account in an appropriate way. In order to model the control strategy from existing experts knowledge the individual components of the structure indicated were implemented using linguistic variables and fuzzy logic rules.

The graphic development tool fuzzyTECH was employed to implement this control concept. Figure 5 shows a section of the main worksheet in which the firing capacity control system is depicted. The symbols here represent rule blocks and interfaces. Each rule block stands for a set of fuzzy rules and the interfaces represent the data transfer to the upstream or downstream mathematical operations.

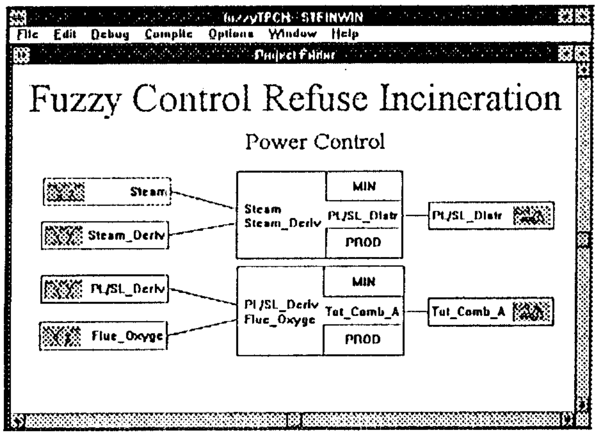

Figure 4: Part of the Structure of the Fuzzy Project: "Power Control"

This optimized fire capacity control system fundamentally ensures a more even combustion pattern. As a result it is possible to reduce the CO content in the flue gas and improve the burnout parameters while simultaneously reducing emissions and in particular the chlorinated organic pollutants therein.

The firing system control circuit introduced here has been developed as a project sponsored by the Federal Minister for Research and Technology.

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