LA-UR-02-3225
*Approved for public release;
distribution is unlimited.*

*Title:*

# A Fuzzy Feed-Forward/Feedback Control System for a Three-Phase Oil Field Centrifuge

*Author(s):*

William J. Parkinson, Ronald E. Smith,
Fred N. Mortensen, Paul J. Wantuck, Timothy Ross,
Mohammad Jamshidi, and Neal Miller

*Submitted to:*

http://lib-www.lanl.gov/cgi-bin/getfile?00852254.pdf

# A Fuzzy Feed-Forward/Feedback Control System for a Three-Phase Oil Field Centrifuge


William J. Parkinson[1], Ronald E. Smith[1], Fred N. Mortensen[1], Paul J. Wantuck[1],
Timothy Ross[2], Mohammad Jamshidi[3], and Neal Miller[4]

Los Alamos National Laboratory, Los Alamos, NM 87545[1]
Department of Civil Engineering[2]
Department of Electrical and Computer Engineering[3]
University of New Mexico, Albuquerque, NM 87131
Centech Inc., Casper, WY 82604[4]



## ABSTRACT

A set of fuzzy controllers was designed and applied to a commercial three-phase oil field centrifuge. This centrifuge is essentially a one of a kind unit. It is used to recover oil from tank bottoms and oil field and/or refinery sludge. It is unique because it can separate oily emulsions into three separate phases, oil, water, and solids, in one operation. The centrifuge is a large but portable device. It is moved form site to site and is used to separate a large variety of waste emulsions. The centrifuge feedstock varies significantly from site to site and often varies significantly during the daily operation.

In this application, fuzzy logic was used on a class of problems not easily solved by classical control techniques. The oil field centrifuge is a highly nonlinear system, with a time varying input. We have been unable to develop a physical-mathematical model of the portion of the centrifuge operation that actually separates the oil, water, and solids. For this portion of the operation we developed a fuzzy feedback control system that modeled a skilled operator's knowledge and actions as opposed to the physical model of the centrifuge itself.

Because of the variable feed we had to develop a feed-forward controller that would sense and react to feed changes prior to the time that the actual change reached the centrifuge separation unit. This portion of the control system was also a fuzzy controller designed around the knowledge of a skilled operator.

In addition to the combined feed-forward and feedback control systems, we developed a soft-sensor that was used to determine the value of variables needed for the feed-forward control system. These variables could not actually be measured but were calculated from the measurement of other variables. The soft-sensor was developed with a combination of a physical model of the feed system and a skilled operator's expert knowledge.

Finally the entire control system is tied together with a fuzzy-SPC (Statistical Process Control) filter, used to filter process and instrument noise and a fuzzy conflict resolution code used to keep the feed-forward and feedback control systems working well together.



## KEYWORDS

Fuzzy Logic; Process Control; Centrifuge; Oil Production; Environmental Enhancement


## 1. Introduction

Centech, Inc. has developed a novel three-phase centrifuge process for the recovery of oil from tank bottoms and sludge. The process was a winner of a 1993 R&D 100 award and it is protected by a 1992 patent [1]. Centech has been in business for over a decade and has used this technology to successfully treat nearly 1,000,000 barrels of tank bottoms and sludge including completion/work over, production, industrial, and refinery wastes. The process equipment is a one-of-a-kind three-phase decanter centrifuge that only Centech personnel can successfully operate. Documented results show that this three-phase centrifuge is capable of separating tank bottoms and sludge into three product streams: pipeline quality oil, water with 2-3 ppm total dissolved hydrocarbon, and landfillable solids [2]. Unlike similar processes, the Centech process can often achieve these separation levels without the addition of any separation-enhancing chemicals. The economic analysis of a field test near Hobbs, NM demonstrated that the revenue received from the sale of the recovered oil negated the cost of the service, resulting in a break-even venture. The reduction in liability associated with the reduction in waste volume was not included in the economic analysis. These savings normally amount to much more than the profit from selling the cleaned oil. However, with dwindling oil reserves and rising oil prices, the money obtained from oil sales can become significant. Figure 1. shows the major components of the centrifuge system.

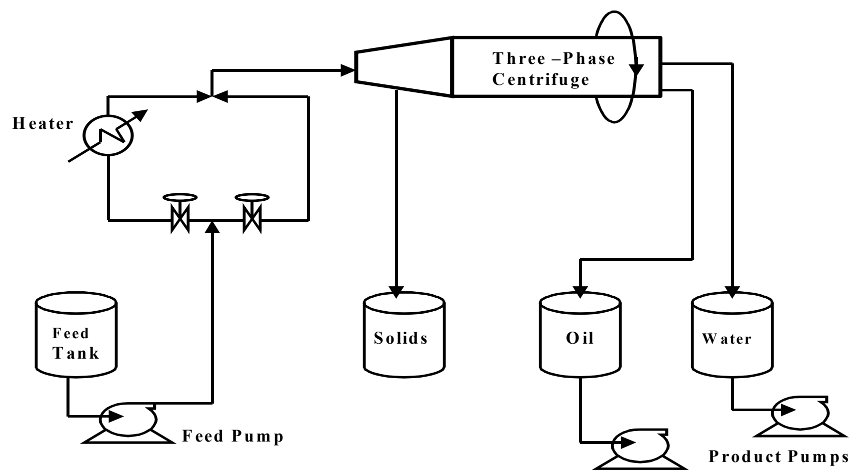


**Figure 1. Schematic diagram of the centrifuge system.**

The main components of the system are the centrifuge, the feed pump, feed heater, and product tanks. Sometimes a feed tank is included in the system, but often the feed is taken directly from waste pit or pond. The three controlled variables are the basic sediment and water (BS&W) in the product oil, the hydrocarbon content of the product water, and the hydrocarbon content of the product solid. The requirements for these variables vary from state to state, and sometimes even from site to site. For example, New Mexico requires the BS&W content of the oil to be 1% or less in order to be pipeline quality. Wyoming requires 0.3% or less. The major manipulated variables that affect this control are the feed pump speed, the feed temperature, the bowl speed, the auger speed, and sometimes dilution of the feed with product water. Unfortunately, the current version of the centrifuge requires that it be shut down in order to change the bowl speed. At the present time most of the control is accomplished by manipulating the feed pump speed and the feed temperature.

The Centech centrifuge is a highly nonlinear multi-input, multi-output system. In addition tank bottoms and sludge differ from site-to-site and tank-to-tank, resulting in unique and varying control parameters for each material processed. Dealing effectively with these conditions requires a great deal of skill. Before Centech can offer this technology globally, at least one hurdle must be overcome. The expertise of the Centech personnel must be encapsulated into an intelligent control system paradigm

In 1994, Los Alamos National Laboratory joined forces with Centech. We designed and implemented a feedback control system for the centrifuge based upon the expert knowledge of the Centech operators. This paper includes the description of a more comprehensive total control system. The resulting expert based control system, through the implementation of fuzzy logic, controls the quality of the oil produced by manipulating only the throughput and temperature of the feed. We chose a fuzzy logic control system for two reasons:

1. The system proved too complex to model adequately for control purposes.

2. It was entirely possible for an expert operator to maintain excellent control of the centrifuge system, under almost all circumstances. The expert's description of his control actions was almost identical to a textbook description of a fuzzy expert system.

We, therefore, chose to model the expert rather than the centrifuge, using a fuzzy expert system.

## 2. The Total Control System.

The total control system combines feed-forward control with the feedback control system as shown in figure 2. The total control system consists of the following items:

- The fuzzy feedback controller
- The fuzzy-SPC filter.
- The fuzzy feed-forward controller.
- The fuzzy soft-sensor.
- The conflict resolution code.

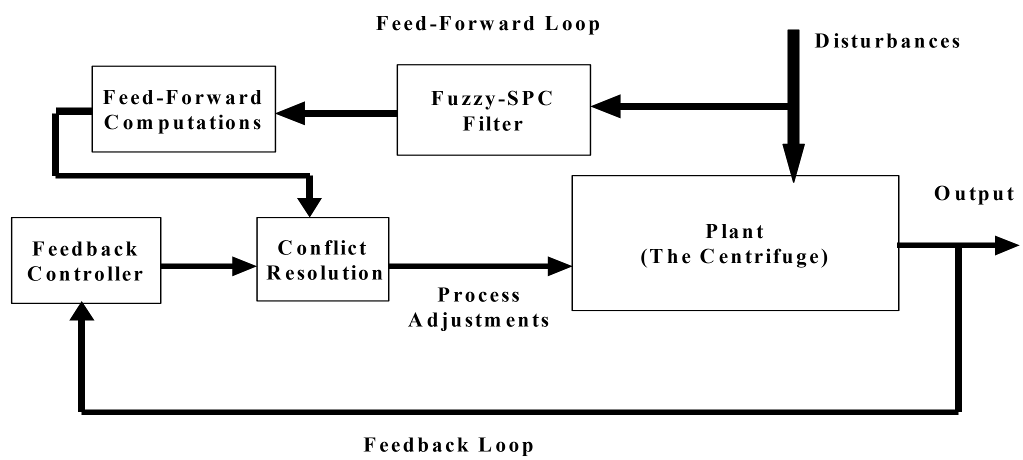


**Figure 2. Block flow diagram for the combined feed-forward and feedback control systems.**

Figure 2. shows the block flow diagram for the combined feed-forward and feedback control systems. This system includes a "fuzzy-statistical process control (SPC) filter" and a conflict resolution program. The feed-forward controller is used to detect large changes in the feed that require process control adjustments <u>before</u> a major problem is encountered with the centrifuge. This is important for proper control of the centrifuge. An example of a condition that requires feed-forward adjustment is when feed material collects in stratified layers in the feed tanks or ponds. The fuzzy-SPC filter is required because the feed signals are quite "noisy". We don't want to make changes to the control variables in advance unless they are truly required. The fuzzy-SPC filter differentiates between noise in the measured feed variable and a true change in the feed.

The feedback control system is continually working, making adjustments to the process after a product change has been detected. The conflict resolution portion of the controller makes sure that corrections to the process due to both feedback and feed-forward conditions are compatible with the goals of both controllers. The feed-forward portion of the controller usually dominates these corrections, because feed-forward events are future events, and only significant events are acknowledged because of the filter. However, some weight is given to current action governed by the feedback controller.

The fuzzy-SPC filter is a rather unique idea used to filter out the sensor noise. It is quite appropriate for the centrifuge system, since the system time constant is in the order of minutes rather than seconds. The technique is compute intensive and would be too slow for a system requiring rapid control action. The fuzzy-SPC filter is based on the Individual and Moving Range charts similar to the X bar-R charts, from the discipline of statistical process control (SPC). Our technique uses fuzzy logic because several variables are monitored at one time, rather than just one, the usual SPC case.

The feed-forward computations shown in figure 2 are broken into two parts, the fuzzy soft-sensor and the fuzzy feed-forward controller. This combination is shown in figure 3.

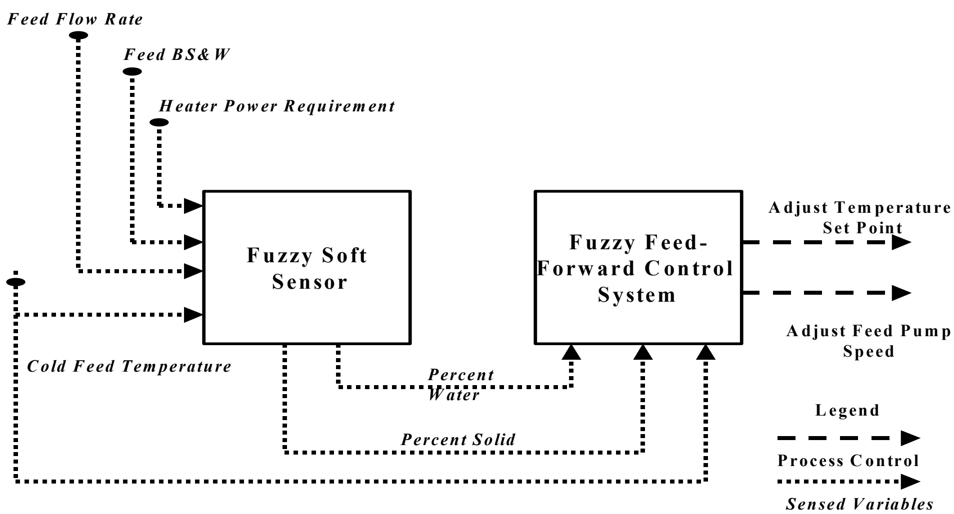


**Figure 3. Flow diagram for the fuzzy feed-forward control system and fuzzy soft sensor.**

The feed-forward control system requires three input variables to determine what adjustments, if any, are required for the feed pump speed (or flow rate) and the feed temperature set point. These variables are the cold feed temperature, percent change of water in the feed and percent change of solid in the feed. Unfortunately we cannot measure percent change of water in the feed or percent change of solid in the feed. We can measure percent change of BS&W in the feed, which is the sum of the water and solid change. We can measure the change in the power requirement for the feed heater to maintain a given set point temperature and we can measure a change in the volumetric flow rate. Based upon these measurements, the feed BS&W measurement and some knowledge of the cold feed temperature changes, our expert can determine what the changes in feed water content and feed solid content are. We put this expert knowledge into the fuzzy soft sensor.

### 3. The Feedback Control System.

The feedback controller is a fuzzy intelligent control system. It is the heart of the total control system. Figure 1 is a schematic drawing of that plant, the centrifuge system. The centrifuge, itself, is a continuous-decanting machine with a helical conveyor (sometimes called a scroll or auger). Spinning the feed mixture at high rpms, creating a large centrifugal force, separates the three phases.

Currently there are only eight rules in the feedback portion of the control system. There are two input variables, ***Product Oil BS&W*** and ***Product Water Oil Content.*** The ***Product Oil BS&W*** variable has four membership functions, *Very High, High, OK*, and *Low.* The ***Product Water Oil Content*** variable has two membership functions, *High* and *OK.* There are two output variables, ***Feed Rate Change*** and ***Feed Temperature Change***. Each of these variables has five membership functions. The membership function names are the same for each variable. The names are *Negative Big, Negative Small, Zero, Positive Small*, and *Positive Big.* The membership functions are in the form of simple triangles and the feedback control system rules are of the form:

If the ***Product Oil BS&W*** is... and if the ***Product Water Oil Content*** is... Then the ***Feed Rate Change*** is ... and the ***Feed Temperature Change*** is...

### 4. The Fuzzy-SPC Filter.

The filter is designed to prevent the feed-forward controller from acting upon feed changes that are really just "noise" in the sensors and the system. It is a fuzzy version of the implementation of statistical process control (SPC) charts known as **Individual** and **Moving Range** charts. These charts were patterned after more commonly used X bar-R charts. Dr. Walter Shewhart [3, 4] developed both types of control charts in the 1920's for quality control. For this work we have modified the SPC technique to include fuzzy logic. The reason for the modification is that the expert operator normally looks for indications that the feed BS&W has changed by a magnitude of at least ± 10% before implementing a manual feed-forward control. The control system can measure this with the feed BS&W meter. However, this is not the whole story. The feed water concentration and feed solid concentration can change in opposite directions, making the feed BS&W reading lower than ± 10%. The feed-forward controller relies on knowledge of the water and solid changes individually not the total BS&W change. The fuzzy soft sensor determines the magnitude of the individual water and solids changes from knowledge about feed pump flow changes and feed heater power requirement changes in addition to the total feed BS&W change. Our fuzzy filter incorporates these three variables into a single variable that we call **Feed-Magnitude-Change** and that is the value used with the SPC technique rather than just the feed BS&W change. In our situation, in the field these charts are developed each workday at the beginning of the run, after steady-state operation is achieved.

### 5. The Fuzzy-Feed-Forward Controller.

The fuzzy feed-forward controller is designed for disturbance rejection. The disturbances come in the form of feed disturbances. The feed disturbances that cause problems are cold feed temperature changes, that is changes in the temperature of the feed stream before it reaches the feed heater, which cause among other things changes in feed heater power requirements. The other disturbance that causes problems is a change in the feed BS&W. Knowledge of the change in the feed BS&W alone is not helpful. The variables that are meaningful are the changes in the percent water in the feed and changes in the percent solid in the feed. The sum of these two changes is equal to the change in the feed BS&W, which is the variable that we can measure. The fuzzy soft-sensor uses the variables that we can measure, cold feed temperature, feed BS&W, feed flow rate change, and feed heater requirements to predict the changes in the feed water and solid content. Figure 4. illustrates the combination of the feed-forward controller and the fuzzy soft-sensor.

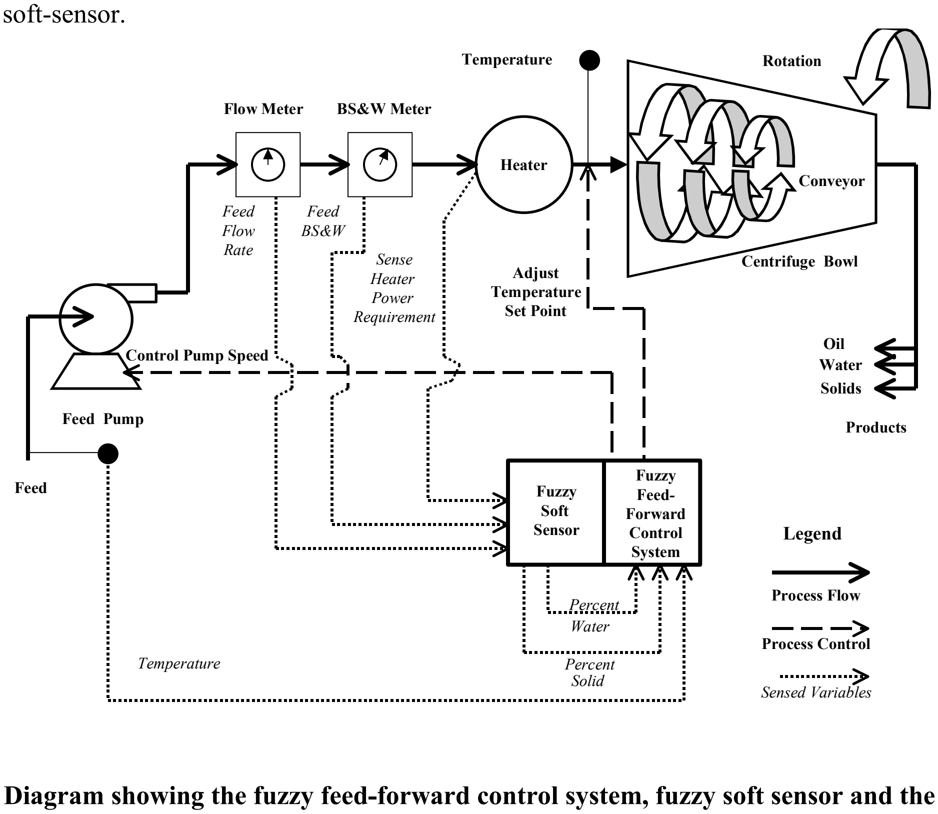


**Figure 4. Diagram showing the fuzzy feed-forward control system, fuzzy soft sensor and the centrifuge system.**

There are 27 rules used by the feed-forward controller requiring, three input variables, nine input membership functions, two output variables, and six output membership functions. The rules are of the form:
If ***Feed Water Composition Change is…***and ***Feed Solid Composition Change is…*** and ***Cold Feed Temperature Change* is…** Then ***Feed Pump Speed Change is…*** and **Feed *Heater Set Point Change is…***

## 6. The Fuzzy-Soft-Sensor and Conflict Resolution Codes

The basic rules for the fuzzy-soft-sensor are of the form:

If the ***Feed Pump Flow Change*** is … and the ***Feed BS&W Change*** is … and the ***Feed Heater Power Requirement*** is … then the ***Feed Water Change*** is … and the ***Feed Solid Change*** is … .

In the case of the fuzzy soft sensor there are several hundred rules. The major reason for using this many rules is that the composition of the feed has a very strong effect upon the rule input variables, especially the *Feed Pump Flow Change.* Up to the point of approximately 67% oil in the feed, water is the continuous phase, a situation where the oil droplets are suspended in the water. For oil compositions above this point, oil becomes the continuous phase. This is the opposite situation, water droplets suspended in the oil. When water is the continuous phase, the viscosity of the oil increases with an increase in oil content. In this region an increase in oil content in the feed reduces the feed pump flow rate. If oil is the continuous phase, an increase in oil content reduces the viscosity and observed system changes are the opposite from the water continuous phase case. For this reason, we need to know which phase is the continuous phase in order to know which set of rules to use. The theoretical transition from water being the continuous phase to oil being the continuous phase is 67% oil in the feed. In practice the transition varies over a range of several percent. The transition point is also affected by the percent of solids in the feed. When we are operating near the transition point we have less confidence in the fuzzy soft sensor and hence want to rely less on our feed-forward controller than when we are more confident in the analysis provided by the soft sensor. The conflict resolution code is a fuzzy rule base that assesses our confidence in the soft sensor results, basically by estimating how close we are to the transition point. This code then weights the control actions from the feedback and feed-forward controllers, based on our levels of confidence.

## Summary and Conclusions

The fuzzy control system has been tested in the field under adverse operating conditions and works quite well. The expert operator feels that the system has gone a long way in the effort to eliminate the total reliance upon an expert operator. This control system is an example of a fuzzy control system that is used in situations where classical control systems cannot be used. This is not a case where a fuzzy control system is used just because it outperforms a classical system.

## REFERENCES


1. Miller, N., (1992) Three-Stage Centrifuge and Method for Separating Water and Solids from Petroleum Products, United States Patent No. 5,156,751.
2. Parkinson, W. J., R.E. Bretz, R.E. Williams, C.E. Polston, and N. Miller, (1993) Centrifuge Technology for Minimizing Petroleum Waste. *International Journal of Environmentally Conscious Design & Manufacturing,* Vol. 2, No. 1, pp. 39-46.
3. Shewhart, Walter A., (1980) *Economic Control of Quality Manufactured Product,* American Society for Quality Control, Milwaukee, Wisconsin.
4. Shewhart, Walter A., (1986) *Statistical Method from the Viewpoint of Economic Quality Control,* Dover Publications, New York.