FISH FARM AUTOMATION

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Abstract: This article presents a control system of a fish farm dealing with intensive fish culture. The control system consists of two parts – automation system and optimization package. The automation system watches and controls environment parameters, fish feeding, etc. and offers more comfort to the maintenance, e.g. in the field of scheduled tasks to be performed or concerning alarms signalling. The optimization part schedules the farm production policy in order to maximize its economic profit. It optimizes which pond will be occupied by which fish, and further actions like fish sales and purchases, selection of optimum food type etc.

Keywords: scheduling theory, combinatorial optimization, automation in aquaculture.

1. INTRODUCTION

Most automatic control applications are based on linear models. They often use PID controls, quadratic criteria (LQG control), frequency domain formulated criteria (H_∞ control). Control community developed theory which allows deep theoretical understanding and detailed analysis of such problems. In spite of the theoretical development, there still appear questions even for these classic linear formulations where their practical application is concerned (robustness, hierarchical control). Moreover, automation engineers often encounter application problems which cannot be covered by the classic control theory. Many practical control problems call for combinatorial optimizations like MLP (mixed linear programming) etc. Computer science engineers often solved similar problems in connection with parallel architectures, multi-server scheduling problems, see (Blazewicz *et al.*, 1993). Also the flexible systems control in robotics are based on non-convex combinatorial criteria, see (Oerlemans, 1994) and (Privault, 1994).

New mathematically grounded heuristic methods emerge to solve this kind of optimization problems: adaptive memory programming (AMP), artificial neural networks, genetic algorithms, tabu search and ant systems, see for example the new book (Onwubolu, 2002).

This paper reports such an application: a fish farm automation project ((Hamackova, 2003), (Svadova and Hanzalek, 2003)). We have solved the fish farm optimal production problem on a finite receding control horizon using the MPC (model based predictive control) idea as described in (Maciejowski, 2002) and (Maciejowski, 1998).

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[1] This work has been supported by the Ministry of Education of the Czech Republic under Project 1M6840770004.

It turned out the problem is formally a linear dynamic control problem with linear target function (farm economic profit) subject to non-convex constrains. We had to cope with this fact using a heuristic approach.

Except of the MPC two versions of a distributed automation system have been realized too. The first one is based on open-source software and implements modern principles of object-oriented design and communication. The second one has been installed at the pilot fish farm with the aim to prove the effectiveness and usability of our approach in practice, using software tools proven in many industrial applications.

The structure of the paper is as follows. The optimization package is described in *Section 2*, the principles of the fish farm operation together with some optimization results are given in *Section 3*. *Section 4* contains the description of the implementation of the control system and *Section 5* concludes the paper.

2. PRODUCTION OPTIMIZATION

The farm control system is a hierarchic structure. Whereas the bottom layers look after temperature, oxygen and feeding management, the uppermost layer is related to economically optimal farm management. This layer is represented by an optimization algorithm, which maximizes the farm economic return per unit time on the infinite control horizon. This economic return is a function of number of fish sold, purchased and kept in the farm at each time instant from now on. It may also be a function of water temperature, food intensity and food type, and a couple of other parameters.

2.1 Model

It is possible, at least approximately, to write down a system of integro-differential equations, which couples the quantities appearing as arguments to the farm economic return. Those equations describe dynamic development of fish distribution functions (fdf), which is an equivalent of distribution functions used to describe many problems existing in physics or mathematics, like probability distribution functions. Fish distribution function value $x(t, k, m, f)$ depends on time t, fish species f, pond k, fish weight m, and possibly other arguments as well. This function value is related to the number of fish having the specific attributes (weight, pond, time, species). Dynamic behavior of the fdf couples the fdf function values at two different instants of time. Clearly the fdf values at time t_2 can be at least approximately (in the mean) predicted if one knows fdf at an earlier time instant $t_1 < t_2$ (1). The prediction is possible only if the numbers of fish sold u_s, purchased u_p and replaced u_d from one pond to any other pond are given. It is advantageous that the mentioned integro-differential equations are linear with respect to fdf.

$$\begin{aligned} & x(t+dt,k,m,f) = \dots \\ \dots = \int_0^\infty & \big[G(t,k,m,w,f,\vartheta)x(t,k,w,f) + \dots \\ & \dots + u_p(t,k,w,f) - u_s(t,k,w,f) + \dots \\ & \dots + u_d(t,k,w,f)\big]\,dw \end{aligned} \tag{1}$$

The operator G in (1) defines the fish growth dynamics. Because the fish tend to grow in time, the values of x for a weight at a time t influence the x values for bigger weights and at times after t. Similarly this operator models the mortality and other effects. The model can be represented in the form of a linear multivariate state space model (2) if one admits only finite number of the fish weights. Nonetheless the model is not linear with respect to parameters like water temperature or food type. These were grouped to vector θ in (2).

$$x(t+T_s) = A(t,\theta)x(t) + B\begin{pmatrix} u_s(t) \\ u_p(t) \\ u_d(t) \end{pmatrix} \tag{2}$$

2.2 Optimization

From mathematical point of view the economically optimal fish farm management can be represented by an fdf. Usually it is a problem to optimize for an object, which is described by an infinite number of values as fdf's are. We have therefore confined the algorithm to a finite-dimensional approximation using finite number of fish weights and discrete time instants instead of real valued quantities. Even the infinite number of discrete time instants existing along the infinite control horizon can be represented by a finite number if we adopt an idea the optimal fish farm behavior converges to a periodic policy. Such representation is advantageous because only finite-dimensional optimization problems can be solved numerically on a computer effectively. The optimization problem is related to the economic profit maximization. This maximization is performed with respect to fdf. But not any found function is a valid fdf. It must satisfy the coupling condition given by the integro-differential equation. Moreover, the fdf values must satisfy a number of other conditions: number of fish must be non-negative and must not exceed the pond capacities. Therefore, one can say the optimization problem is constrained and the constraints are defined by both linear equations and linear inequalities (linear with respect to fdf). Because the profit P is proportional to the number of fish as in (3), we have found the optimization problem is an example of linear programming problem described by a number of parameters (sale prices w_s, purchase prices w_p, keeping prices w_x).

$$\begin{aligned} P(t) = \sum_{f,k} \int_0^\infty & [w_s(t,k,m,f)u_s(t,k,m,f) + \\ & - w_p(t,k,m,f)u_p(t,k,m,f) - \\ & - w_x(t,k,m,f)x(t,k,m,f)]dm \end{aligned} \qquad (3)$$

Linear programming problems are very well analyzed and effective numerical packages do exist to solve large-scale LP problems.

2.3 Non-convex constraint

Unfortunately there is yet one constraint, which is represented by neither linear equation nor linear inequality. This constraint is related to the fact only some fish can share the same pond. It can be easily proven that such constraints can be represented by linear equations, which are not required to hold simultaneously, but certain subset of them must hold (either of a class of subsets). Geometrically such constraints are represented by a non-convex subset within the fdf set. The problem, which subset of equation should hold, cannot be resolved easily due to the huge number of those possible subsets. In fact the number of possibilities how the ponds can be assigned for various fish species and weight categories during various periods of time is overwhelming. Such combinatorial problems are quite difficult to solve and this is the reason we had to develop a complex iterative algorithm, which operates with convex subsets of the non-convex set describing those non-convex constraints. To illustrate the preceding statements more clearly we give the following description.

The set of constraints K_1 is initialized with those implied by ponds capacities. Then linear programming algorithm is run to find profit P_1. This profit is bigger than the actually achievable profit, because a number of constraints was neglected. The optimal solution $\{x^{t+1}_{t+H}\}_1$ is then analyzed. The algorithm separates $x(t{+}1)$ and calculates optimal feasible distribution of the fish represented by this fdf. It appears that some fish may not fit in. In other words: $\{x(t+1)\}_1$ must be modified to $\{x(t+1)\}'_1$. Then an inequality constraint $x(t+2) \leq \{x(t{+}1)\}'_1$ is added to the set K :

$$K_{i+1} = K_i + \{x(t{+}i{+}1) \leq \{x(t+i)\}'_i\}. \qquad (4)$$

Afterwards the linear programming algorithm is called again to calculate $\{x^{t+1}_{t+H}\}_2$ – the second iteration ensuing a profit $P_2 \leq P_1$. The third iteration already considers a new constraint $x(t+2) \leq \{x(t{+}2\}'_2$. The set of constraints grows during the iteration process. Hence, the profits must be non-increasing sequence $P_1 \geq P_2 \geq \ldots P_H$. Each iteration i searches for maximum profit over a subset of the set considered by the previous iteration $i{-}1$. Thus at the moment we cannot find the best solution, but we can approximate it and can estimate the maximum possible loss. As long as $(P_1 - P_H)/P_H$ is a small number $\leq 10^{-1}$, the profit P_H can be taken as a close approximation of the global optimum point.

2.4 Feedback optimization

So far we have explained the uppermost fish farm control algorithm layer is based on an optimization problem solution. This optimization provides a fdf, which defines the number of fish sold, purchased, replaced from any pond to the other and so on, at every time instant from now on. Such farm strategy leads to the maximal profit per unit time on an infinite horizon starting from the actual farm state. If the farm management decides to pursue this strategy, the farm fdf will soon develop to values deviating from the found optimal ones. The deviations are due to random fish mortality, random fish growth rate, random sales etc. One possibility to fix the deviation is the fdf recalculation. Periodically updated optimal fdf then reacts to the random disturbances, market price changes, or random sales due to sales which were planed but never realized. Such periodic recalculation is known as receding horizon strategy control. This receding horizon strategy is used by the model predictive controllers, which became very popular in industrial applications during the last decade (see e.g. (Maciejowski, 2002)). Thus the optimization layer is nothing than a feedback multiple-input multiple-output controller, which senses the current fish distribution function value and produces the recommended control action which consists of the recommended sales, purchases, fish redistribution among the ponds, and also food type, intensity, etc. The economic return feedback maximization steers the fish farm to the optimal strategy. The random effects, in contrast, deviate the farm state from the optimal trajectory. The periodic recalculation then compensates for those disturbances. The control algorithm should stabilize the farm state close to the optimum without any help from the farm management. It just writes out a table of recommended control actions.

2.5 Information representation

To perform the calculations required the algorithm needs a considerable amount of information to know. Firstly it is the actual farm state, which must be watched by the personnel and rendered in the electronic form manually. The algorithm also requires information about fish growth rates and mortality for various fish weights, various months of the year and for various expected market prices, feeding costs etc. It also has to know which fish species and weights can be kept together. All those items of information are kept in database tables and selected just in time via appropriate queries sent to the database server. Then the multidimensional table interpolation is used to obtain values for arguments not present in the database. The values obtained via interpolation then modify the optimization problem parameters.

3. FISH FARM OPERATION

At this point, we are about to describe basic operations which must be done by the personnel at the farm to ensure correct fish distribution in the ponds. The following list does not include operations, however, which are of kind of ordinary maintenance such as providing food, checking correct values of environmental quantities, etc.

- The fish in each pond must be weighed regularly in order to select those which grow more rapidly than the others. Such fish must be moved to another pond.
- The farm operations such as sales, purchases and fish are planned in advance.
- The amount of heat energy supplied to the water in the ponds must be decided upon because some fish species grow more rapidly in warmer water. On the other hand, the expenses increase with higher heat energy.
- The growth rate of the fish depends on the food type as well. The food manufacturers provide their products with a detailed description how to feed the fish in order to ensure their optimal weight gain. Nevertheless, the farm personnel must decide which food to choose and how to suit it to the actual farm conditions.

We have developed our controller with respect to the above mentioned issues in order to minimize the human factor in the process of farm-operation decision taking. Some tasks such as fish weighing and moving among ponds cannot be done automatically but their timing can be planned more accurately according to the current farm conditions. In other words, the information about the current farm state is determined by the personnel and input into the controller which consecutively computes corresponding control actions. Similarly, the actions cannot be performed automaticaly because the final decision possibility must be left to the farm management. The controller itself does not and even cannot have enough information to work completely autonomously. Thus the personnel is taken as the controller feedback and output at the same time.

3.1 Optimization Case Studies

We have defined a simple example: the farm consists of 3 ponds, each of capacity 60 kg fish. The optimal cycle is one year long and the sampling period is one month. The total gain of the farm in the one-year cycle is 251,007 CZK and some of the actions to be performed on April 1st are shown in Table 1.

Table 1. Cutout from one-year cycle

Market	pond1	pond2	pond3
	...		
	Apr-01-2004		
-4528 CZK 566 fish, 0.075 kg	→ ● 417 fish 0.144 kg		
11676 CZK ● ←	417 fish 0.144 kg		
-4528 CZK 566 fish, 0.075 kg		→ ● 417 fish 0.144 kg	
11676 CZK ● ←		417 fish 0.144 kg	
-4528 CZK 566 fish, 0.075 kg			→ ● 417 fish 0.144 kg
11676 CZK ● ←			417 fish 0.144 kg
Occupancy:	60 kg	60 kg	60 kg
	...		

In column Market, sales and purchases are given indicating 566 fish of 0.075 kg are to be bought into each of the three ponds whereas from every pond 417 fish of 0.144 kg are to be sold. These transactions cost 4,528 CZK each and gain 11,676 CZK each, respectively. All ponds are fully occupied. Several qualities of the results are worth mentioning.

- The transactions from the table repeat every month, i.e. every month 566 small fish are bought and 417 bigger fish are sold. Such evolution is given by the growth data (the fish put on 1.5 g each day) and by the mortality (1% of the fish die every day).
- No fish redistribution is necessary since all fish are in their respective ponds no longer than a month.
- It is optimal not to breed larger fish. According to the economic data the sale price increase is the biggest between the smallest and

the second smallest weight category and thus the farm profit is the biggest when breeding such fish.

This example led to a different policy than expected: instead of breeding little fish until they would reach some optimal weight to sell them, the farm should buy fish to sell them after one sampling period. This happens whenever the manipulation costs are neglected or underestimated. Most of our fish farming partners received this kind of policy for their first trial optimization process.

4. CONTROL SYSTEM

The actual realization of the control system was done concurrently at two sites: a test implementation at the university and an implementation at the pilot farm. Different approaches were applied in both cases, each using completely different principles of the control system. The test implementation was done with the aim to use open-source software in as a great extent as possible whereas the other system uses hardware and software equipment well-proven in industrial applications. However, the data acquisition from the sensors is performed in a common way and thus via the RS-485 line and a simple character-oriented protocol. Moreover, both sites must run uninterruptably, otherwise the fish lives could be endangered. Big attention has been given to the alarm evaluation and diagnosis, especially at the pilot farm. Thus an instant Internet access to the site is provided as well as the alarm signalling over GSM.

In the following paragraphs the individual implementations are described.

4.1 Fish demonstrator implementation

At the DCE a demonstrator of the recirculation system was installed consisting of three ponds as can be seen in figure 1. Is is a simplified model possessing the same principle features as a real fish farm. These principles include measurement of important environmental parameters (pH, temperature and dissolved oxygen), automatic heating, fish feeding and oxygenation/aeration, and mechanical and biological filtering. From the point of view of the control system there are important differences. At the demonstrator, the control system is based on a DimmPC with Linux operating system showing a low-cost open-source implementation. ACE library ((Schmidt, 2004)) was selected as a means for object-oriented controller design and for the encapsulation of operating system calls. Because of the library's availability for a variety of operating systems, our implementation of the controller is platform independent. RS-485 and Ethernet interfaces are at disposal at the computer as well, having allowed us to realize the communication easily.

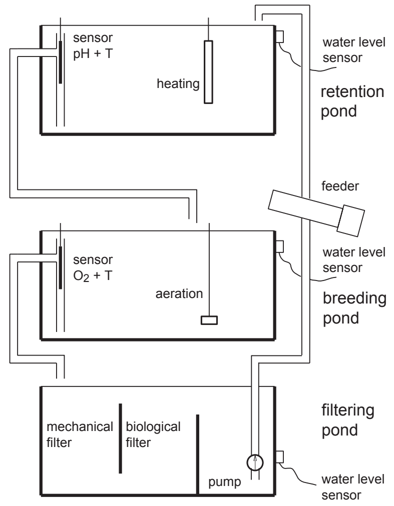

Fig. 1. Recirculation system

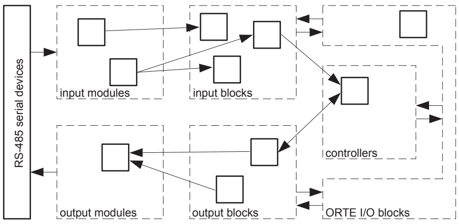

Fig. 2. Controller structure

Controller design The structure of the controller can be seen in figure 2. The main control loop of the control algorithm is executed periodically using Posix interval timers. This fact enables the algorithm to set the sampling period and execute always one cycle of the loop upon arrival of the timer signal.

The individual parts of the control program are implemented using objects, which are based on the ACE library (see (Schmidt, 2004)). The objects can be divided into several groups as depicted in figure 2. The *modules* are devices connected over RS-485, which is represented by the *serial device*. The *data blocks* (input/output) encapsulate the process variables and their structure was inspired by the function blocks defined in the Profibus PA profile. The *controllers* perform the actual control algorithms, the *jobs* (not depicted in figure 2) carry out single tasks schedulled for certain time of day such as feeding or lighting. The *ORTE blocks* are used to communicate data with the superordinate control system.

Ethernet communication The Real-Time Publish/Subscribe (RTPS) protocol has been used. The implementation of the protocol, used in our application, is primarily designed for transfer of variables in real-time using the UDP protocol. The mechanism of publisher/subscriber model is utilized. Thus, the direction of the data transfer is unidirectional, always from the publisher to the subscriber. This protocol has several advantages:

- Publications and subscriptions are selected at the configuration phase and the protocol takes care of the rest. Primarily, the process variables take part in this data exchange.
- Publishers and subscribers can be arbitrarily added or removed without any change in the software. This feature could be used in later extensions of the system if we wanted to transfer data over the Internet to several PC stations.
- There are implementations for Windows and Linux so that this protocol can be easily used for our purpose. It means that the Windows implementation enables us to adapt the data to an industrial standard of data transfer to operator stations.

In our case, publications are used to send process and status data, and subscriptions are used to receive commands. The adaptation at the Windows side is done in the form of an OPC server.

4.2 Implementation at the Farm

The pilot farm at the RIFCH consists of 18 ponds connected in a recirculation system. Commercial software called DisCO is used for data acquisition, process control and visualization. The structure of the system is similar to the one used at the demonstrator, just the implementation of the oxygenation controller requires more complicated approach. This is caused by the nonlinearities of the oxygen distribution from the jets in the water pipes to the ponds.

5. CONCLUSION

We have presented the fish farm automation project. The hierarchic control system consists of several layers spanning from the bottom layer, which takes care of the water flow control, to the uppermost farm revenue optimization layer. Each layer required specific problems to be solved. The water parameters control success dwelt mainly on system instrumentation. The revenue optimization, in contrast, was found to be a non-convex optimization problem. A heuristic approach was proposed to overcome this difficulty. We stress the fact though the method does not find the global maxima, it provides an upper estimate of the globally optimal revenue. Thus, one can see how much the revenue could be possibly increased if the ideal optimization algorithm would exist. The control system was designed with respect to the fact the fish die within few hours in case of its failure. Therefore it is hierarchic: still works if a portion of hardware fails. For the same reason it is capable to send alarms via GSM network etc. Nowadays fish farms are not automated to this extent.

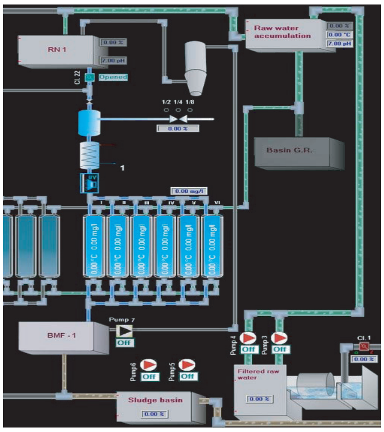

Fig. 3. Six ponds at the farm

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