Mathware & Soft Computing 6 (1999) 125-139

An Example of the Knowledge Based Controller - Design and Evaluation

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Abstract

Knowledge based controller for a balance control model is presented in this paper. The design of the controller was based on the human control of the same process. Developed controller is tested by means of simulation and operation on the laboratory balance control model. The simulation results of the controller as well as a statistical description of the experiments with developed controller and human control is presented in the paper. Verification is based on experiments with an intelligent controller and a human control of the same plant. The results obtained with the developed intelligent controller (set up time, control error, speed, speed range) are satisfied and similar to the results of human control.

1 Introduction

Our experience shows that conventional controllers (such as a PID) can handle only the very limited domain for which they are designed. Outside this domain they are more or less useless. However, human beings often successfully handle the same task on much bigger domain. Therefore we started an experiment using a laboratory balance model, with the aim of confirming this belief. We have tried to develop a controller with more human-like capabilities!

We started with analysis of the human control to learn from it and to design the controller. We carried out simulations and experimented on a real plant. At the end, we evaluated our controller. We used human control results and implemented controller results for verification of the controller. We considered characteristics: settling time, control error, reel sped and speed range. Knowledge based controller acted similar to a human being, but has a similar disadvantage too: relatively big control error. However, we did reach a compact state space representation, as well as a compact and fast program code for the controller. It has non-linear static characteristics. The development process and final qualitative controller are closer to expert systems technology than to fuzzy technology. The developed controller can be classified among intelligent control systems.

2 Qualitative Representation

Certainly it is important to present some aspects of qualitative representation and the use of qualitative models in the process control.

Modeling is a procedure in which part of the real environment is represented by a model that includes all essential properties of the modeled object. With classical mathematical models, all treatments offered by mathematical procedures are possible. Models of the processes and devices are described by systems of differential equations. Also, the time responses of all state variables can be calculated provided that the initial conditions are known. The complexity of the representation increases rapidly with the complexity of the modeled object, or with the details of its presentation. We must also deal with systems that are too extensive for simulation, in particular, for real time processing. One of the possible approaches is to present the objects qualitatively. A presentation of this kind is reasonable since we know that the results of numerical simulations often require a qualitative interpretation.

The fundamentals of qualitative inference and the foundation for practically all of the relevant research are given in the works of Forbus [3], Kuipers [6], and De Kleer and Brown [2]. The purpose of qualitative inference is to create and use simplified presentations of the world, leaving out the irrelevant details, but retaining the resolution and the interpretation of the important properties of behavior.

How do we represent the state of the system? In continuous mathematics, the values of the variables are taken from a set of real numbers, but the qualitative presentation breaks this space into a finite set of intervals called quantitative spaces. The value of the variable is given by its position in the quantitative space inside the interval or on the boundaries between the intervals. The simplest quantitative space includes only the boundary zero. The variable can adopt three values: it is on the boundary, higher or lower on the interval. If the boundaries are values where important events occur, we call them landmark values. Apart from determining the values in the quantitative space, the state variable also determines the direction of change (typical examples are the increasing, decreasing, or steady states). The direction of change indicates the landmark that the value is approaching. State transitions are when the states of variables are changing. The direction of the change assures the connection between the structure and the behavior, thus making the prediction of state transitions possible. Physical laws tell which combinations of state variables and which directions of changes are valid, and which transitions are possible.

Advantage of using qualitative representation and inference in process control is the efficiency of these systems. Their main advantage is compact knowledge representation. They have also advantage in specific applications where only qualitative information is available because measurements cannot be performed, or when continuous sensors are supplemented with discrete indicators. Sometimes the methods

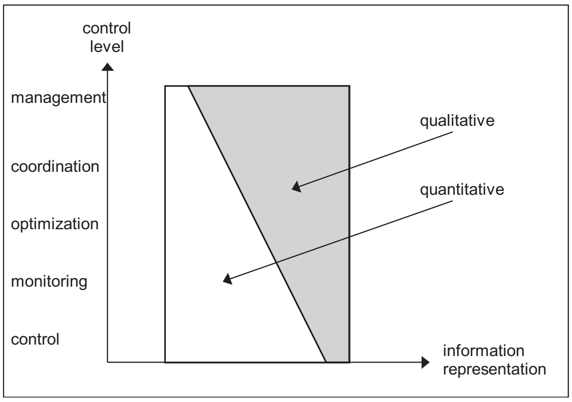

Figure 1: Portion of the quantitative and qualitative information required for the process control.

of qualitative inference can be used to avoid time consuming numerical computations, particularly in cases when the accuracy of input data is not assured.

We used qualitative representation on control level. But methods of qualitative representation and inference sometimes cannot satisfy the requirements of first control level: the control level [5]. Nevertheless, already on the next level, the monitoring level, they are a useful supplement to classical approaches. Their efficiency increases with the increasing complexity of the control level. We can present portion of the quantitative and qualitative information representation in the process control with figure 1.

3 The Qualitative Plant Model

It is necessary to adequately present the state variables of the production plant in order to design the controller properly, and to control the plant to reach the desired state.

One of the principal objectives of qualitative modeling is a simpler presentation of the problem than that obtained through continuous functions. In a continuous representation, the variables can be any real number, whereas in a qualitative representation the space is divided into a finite number of intervals called quantitative spaces. The value of the variable is given by its presence in the quantitative space. The simplest quantitative space has only one boundary and allows the variable to have three values. It can be on the boundary (0), on the interval above it (+), or on the interval below it (−).

We have modeled the motion of the reel on the balance control model. In our experiment, we used a laboratory model in which we positioned a reel on a bar, as shown in figure 2.

A very simple mathematical model of the controlled system can be derived if

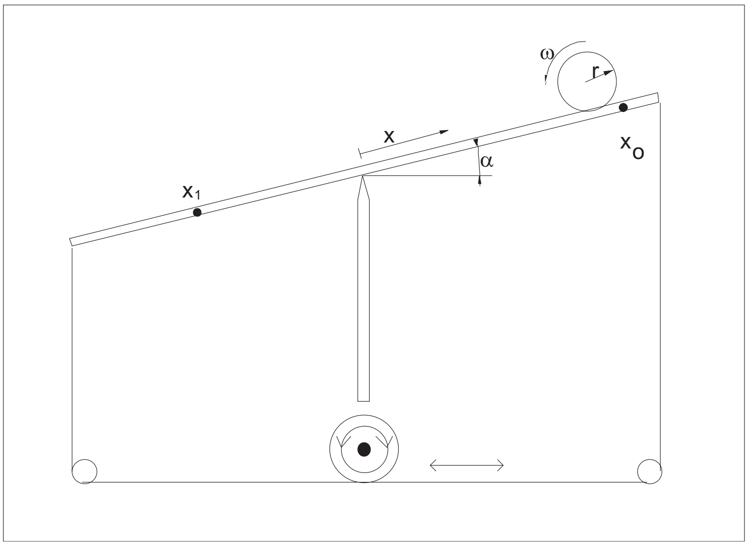

Figure 2: Schematic representation of reel motion on a bar.

small changes of the bar's angle are assumed. First, let us describe the reel's motion on the bar. We assume that:

- the equation of pure rotation is: $\omega r = -\frac{dx}{dt}$,
- the inertia of the reel is: $J = \frac{1}{2}mr^2$,
- the friction of rotation is neglected,
- it holds for small angles: $\sin\alpha \cong \alpha$,
- and the centrifugal force acting on the bar is neglected.

Thus, the simplified equation of motion is: $\frac{d^2x}{dt^2} = \frac{2}{3}g\alpha$.

x denotes the position of the reel on the bar.

We did not derive a qualitative model from the mathematical model of the reel moving. The position of the reel, its speed and its acceleration represented the qualitative space. The qualitative state variables could be influenced by the angle of the bar. The choice of quantitative spaces was essential for the success of further work, which became evident in the design of the controller.

Only one boundary value was chosen for the position. This value represented the delimitation between the intervals and agreed with the real numbers in the space of numbers, which was the desired value. In the case of our implementation, this value could be changed dynamically. On the basis of our careful observations of control by a human, we have decided that this boundary should also be the interval. By doing this, we risked the danger of static control error, but have gained a lower dynamic near the desired value. This can be shown as the controller output $= 0$ on the laboratory model inside the chosen interval near the desired value. The value of the state variable x was: $x \in \{-, 0, +\}$.

The second qualitative state variable, the speed, also had only one boundary value in the beginning. This was the standstill point. Later it became obvious that two boundary values had to be added, namely, the points at which the speed was still safe and the system controllable. Another reason for doing so was an experiment that clearly indicated that a speed exists which represents the limit of successful control. Consequently, the value was: $\dot{x} \in \{--, -, 0, +, ++\}$.

In the same way, acceleration has been limited. The limit is the point showing that there is no acceleration. The reel acceleration interval is denoted by $+$, and the braking interval $-$. Thus, we could write: $\ddot{x} \in \{-, 0, +\}$.

It should be noted that in the implementation the limits 0 were intervals of speed and acceleration.

4 Knowledge Based Controller

In the designing the controller we used the knowledge about: control by a human of the same system, the mathematical model of the plant and the experiences gained in the operation of prototype controllers.

We assumed that we could develop and implement a controller that can behave as human being in the same circumstances. We will define more precisely, what properties of the developed controller should be considered. The key to verification and validation is to develop requirements, and prototype experiments are a way to derive relatively specific requirement statements for the controller operating.

Interesting dimensions of the controller action are: settling time, control error, maximal speed and speed range. We defined settling time as time from begin of the experiment to the time when the testing person was satisfied with the obtained position. Control error is the difference from the actual position of the reel and the desired position after settling time. Control errors were first of all consequence of insufficient sensing by human control and the anomalies in shape of the reel. Maximal speed and speed range describe moving of the reel.

Basic intelligent controller development stages in our case are: problem determination, modeling of the controlled plant, observing of the human control, controller design, simulations of the intelligent controller, experimenting on the real plant and finally, delivery of the intelligent controller (see figure 3). In general, parallel development paths could be substituted with only one option.

In the design of the controller we have predominately used the knowledge about: control by the human of the same system, the mathematical model of the plant and the experiences gained in the operation of prototype controllers. Consequently, the final system is classified among knowledge based systems.

The control algorithm was composed of two basic procedures:

* determining the qualitative states of the system, and

* finding the appropriate control actions.

The first procedure was closely related to the model of the plant. Its task was to determine the qualitative state of the controlled system, in our case, the components of the state vector $X = \{x, \dot{x}, \ddot{x}\}$. The state vector determined the control action and served as a basis for all subsequent decisions of the system implementing the control. This was the reason that it must be designed so carefully.

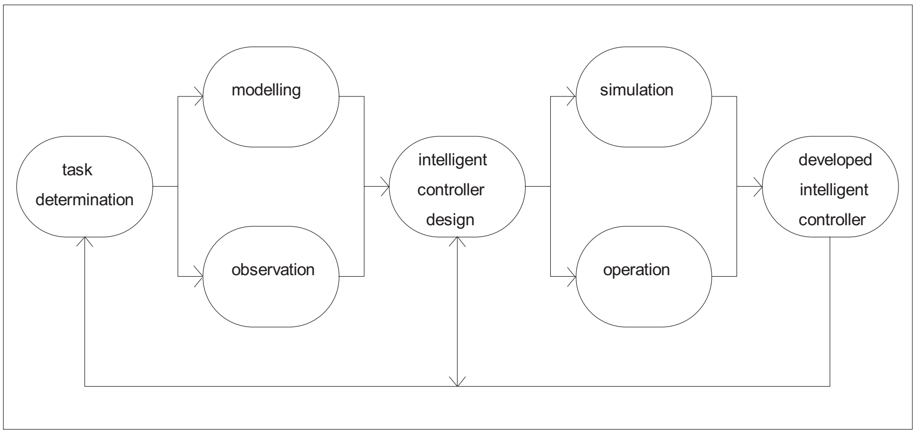

Figure 3: Intelligent controller development stages.

The second procedure provided an appropriate control action concerning the state vector X and the knowledge base. In our case, we simply coded the knowledge, as is described in a following section.

4.1 Knowledge Representation

In our case, the representation of knowledge was based on rules. However, due to the specific properties of the system, it was possible to present the knowledge more clearly with a decision tree, or in a more condensed form, with a matrix, which permitted simple coding.

A part of the rule-based knowledge expression was:

```
if X == (0,0,0) | (0,0,+) | (0,0,-)
    then action = 0;
else if X== (0,+,0)
    then action = -;
else if X== (0,-,0)
    then action = +;
else if ...
```

Very quickly this expression became unclear, so a decision tree was used. It consisted of four levels: the position, speed, acceleration and decision level. The number of qualitative states in each level limited the number of individual nodes. A part of the decision tree is shown in figure 4. The output value was given in each leaf of the tree.

However, the most condensed coding of knowledge was obtained by using the three-dimensional matrix. The number of elements of individual dimensions depended on the number of possible qualitative states. The elements of the matrix contained the value of the control action.

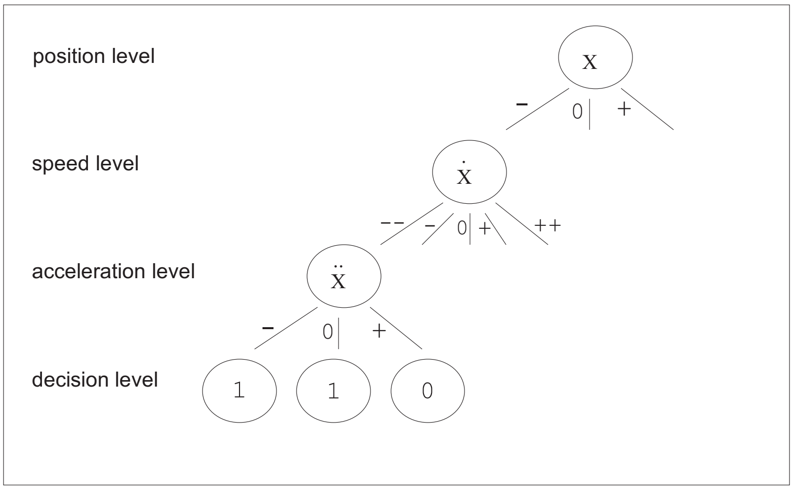

Figure 4: A part of the decision tree.

4.2 Simulations of Controller Operation

The presented simulation results were obtained through the plant simulated by using a mathematical model, and the controller's knowledge represented by a matrix.

To prove the controller's static non-linearity, only two qualitative state variables were assumed: the position and the speed of the reel. In figure 5 the controller's output is shown as a function of position and speed. The values have been chosen to make the interesting part of the static characteristic of the controller clearly seen. The width of the zero interval for the position was 2×0.012, and for the speed 2×0.018. Both state variables could have three qualitative values.

It was evident from the static characteristic that we designed a non-linear controller. The final controller would have a similar characteristic, but it was difficult to present it in three-dimensional space because of the three independent state variables and the one dependent variable.

The following figures show the simulation results of the developed controller. All parameter values are equal to those of the laboratory model test. Figure 6 gives the phase diagram, whereas figures 7, 8 and 9 show the time responses of the state variables. A matrix of size $(3 \times 5 \times 3)$ has been used for representation of the knowledge. The initial position $x_0 = 0.2$ m, whereas the desired one was $x_1 = -0.1$ m. The sampling time was $t_0 = 55$ ms.

4.3 Laboratory Model Control

Figure 10 shows the control of the reel with the developed intelligent controller. Table 1 presents experiments on the laboratory model. Developed controller controls a reel on the bar moving. Histograms on figure 11 present the results of 12

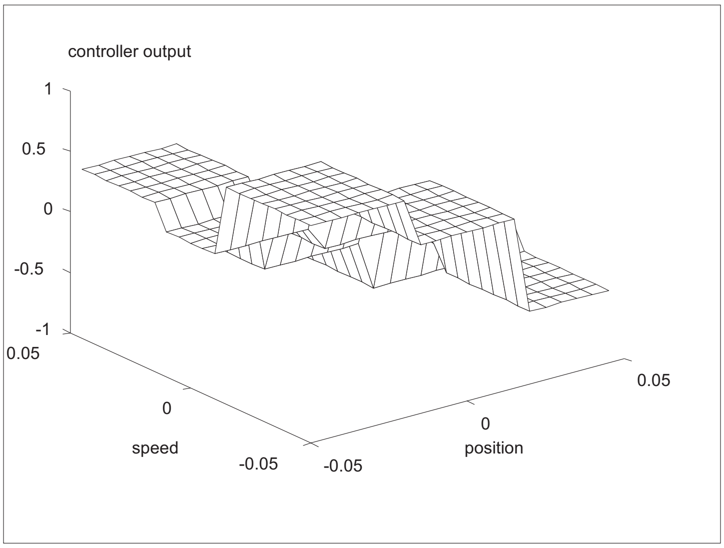

Figure 5: The controller's static characteristic.

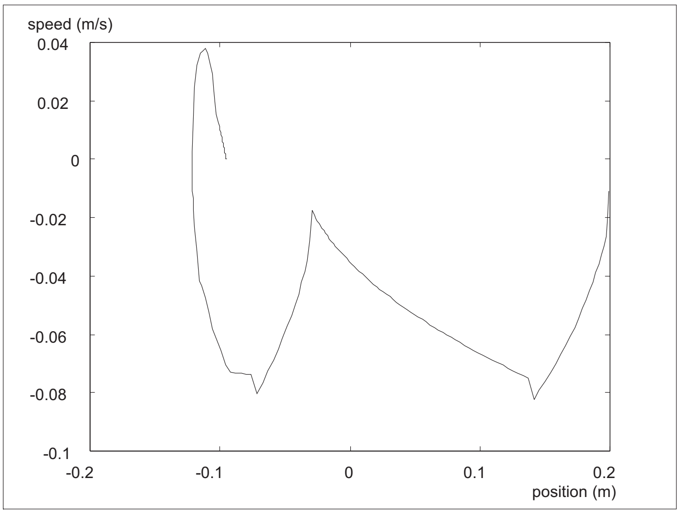

Figure 6: Phase diagram.

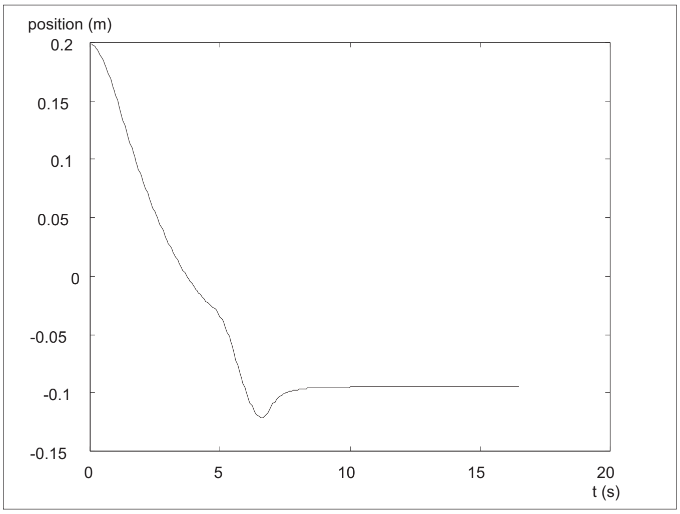

Figure 7: Position diagram.

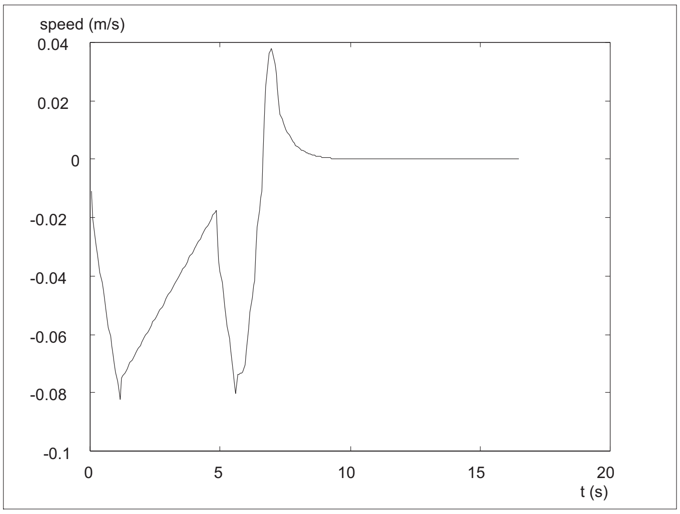

Figure 8: Speed diagram.

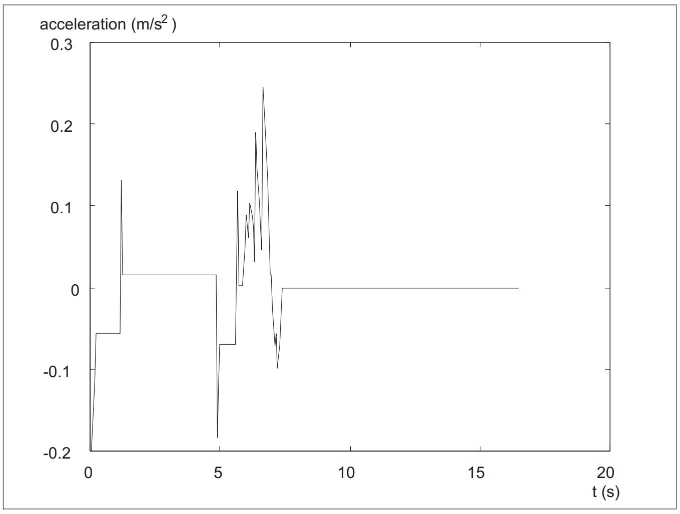

Figure 9: Acceleration diagram.

automatic control procedures.

5 Evaluation of the Intelligent Controller

Intelligent control systems development methodologies do not offer explicit means by which to prove developed intelligent systems. Many elements of a verification and validation methodology exist but these elements have not yet been assembled and standardized. Formal validation occurs within the development cycle. Informal validation employs ad hoc methods and is typically done at the end of development. In the validation process of the intelligent controller, simulation is commonly used

Table 1: Statistical presentation of the experiment with the developed controller.

	Settl. time (s)	Control err. (m)	Max. speed (m/s)	Speed range (m/s)	Square err. (m·m·s)
Mean	17,77	-0,00167	-0,12500	0,20073	0,06521
Median	16,7	0	-0,13636	0,18181	0,05566
Mode	16,7	-0,01	-0,13636	0,18181	#N/A
St. Deviation	4,82	0,00835	0,09117	0,05954	0,03991
Variance	23,19	0,00007	0,00831	0,00355	0,00159
Range	14,94	0,02	0,40908	0,227	0,12865
Minimum	11,21	-0,01	-0,31818	0,13636	0,00871
Maximum	26,15	0,01	0,0909	0,36336	0,13736
Count	12	12	12	12	12

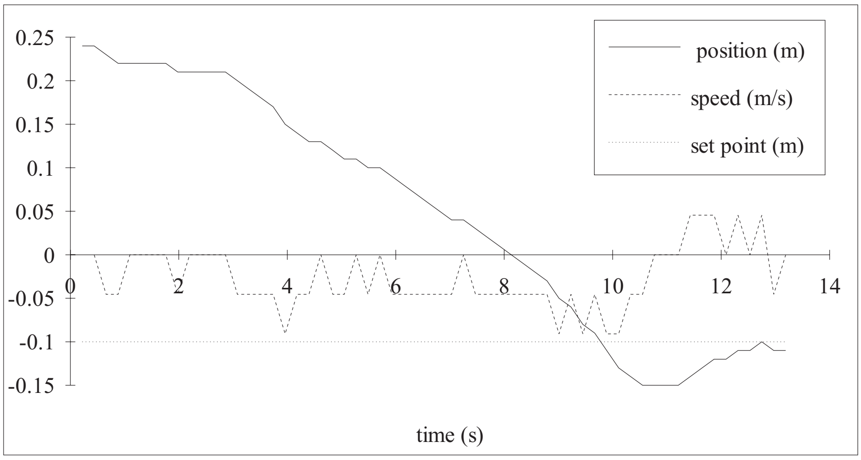

Figure 10: Position and speed diagram for controlled reel.

[7]. The importance of evaluation through simulation cannot be ignored, but actual implementation will often have even more advantages [4].

We developed and implemented a controller that can be considered an intelligent controller because its structure results from the way in which a human being performs a control task [1] [8].

According to the definition of the intelligent control we verified that developed controller is an intelligent controller. We used human control results and implemented controller results for verification of the intelligent controller. We considered the settling time, control error, reel sped and speed range.

Since an intelligent controller represents human knowledge, we must justify its representation level through validation. Intelligent controller validation is testing it to ascertain whether acceptable performance levels were achieved. Performance validation could be performed by running test cases and comparing results with known human results or against controller specification.

We are validating the final result. Intelligent controller is validated against known results. Documented previous control procedures are available for use in validation in our case.

The performance level acceptable to users is called the acceptable performance range. It is specified during development process. In our case, range of the control error from the human control of the plant specifies acceptable performance range for the knowledge based controller. The intelligent controller is designed for a balance control model. An intelligent controller can only be tested for validity on that plant and for an acceptable performance range related to the system's intended purpose.

We performed a qualitative validation that employs subjective comparisons of performance. This does not imply that such approach is informal. Quantitative validation employs statistical techniques to compare system performance with hu-

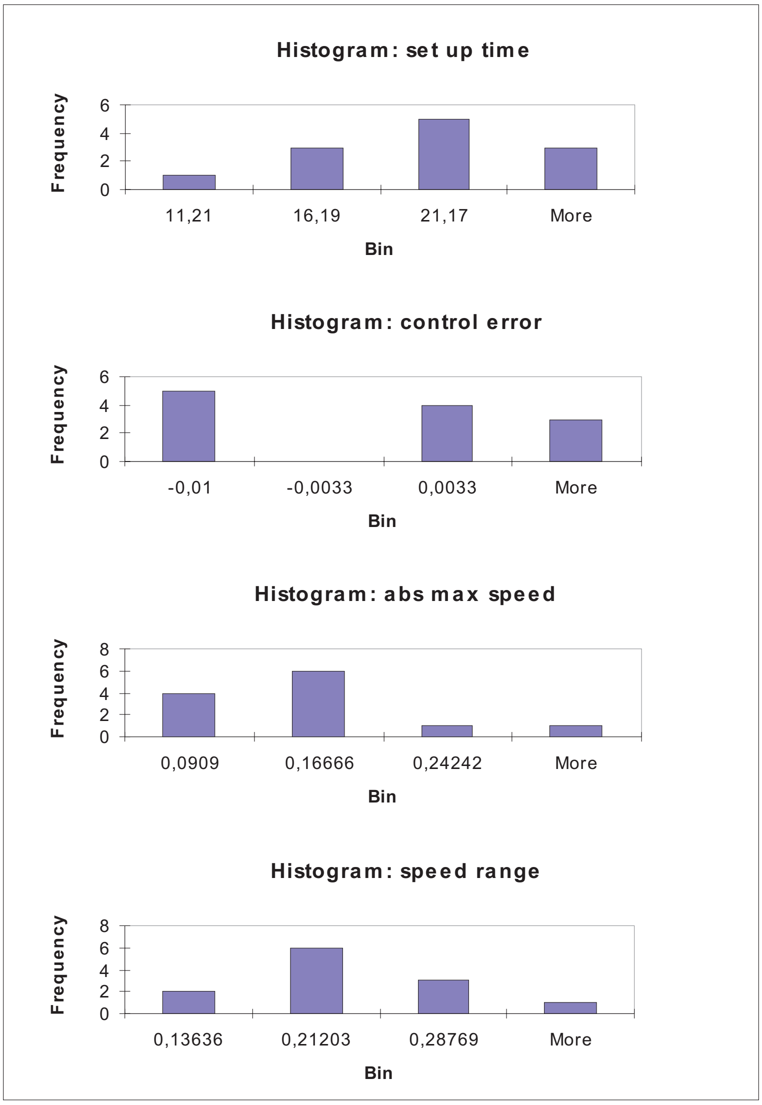

Figure 11: Histograms of the automatic control.

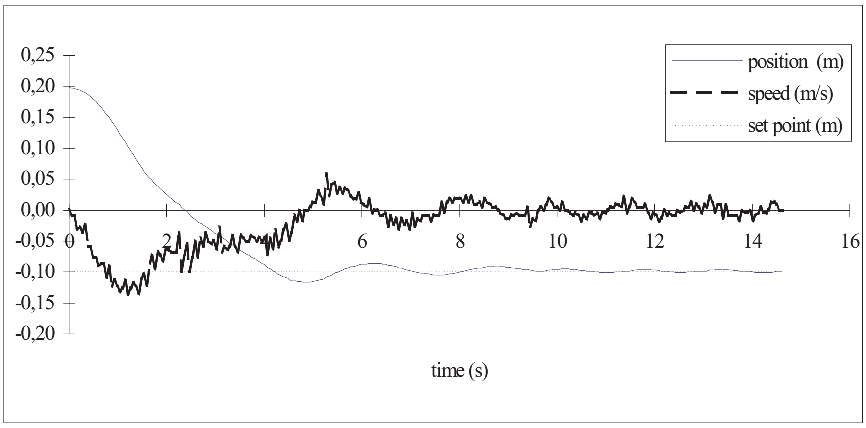

Figure 12: Position and speed diagram for controlled reel in case of human control.

man or required system performances. Qualitative and quantitative methods can be combined as in our case. Developed controller response can be quantified and quantitative or statistical methods can be used.

We combined two qualitative validation approaches: predictive validation and field tests. Predictive validation requires using historic test cases, and either known results or measures of human performance on those cases. Intelligent controller results were compared with corresponding results obtained from human control. Field tests place an intelligent controller in operation in a real plant and then seek to perceive performance errors as they occur.

Table 2 and histograms on figure 13 show results of the human control. Test persons act on the process model spindle.

Table 2: Statistical presentation of the experiment with the human control.

	Settl. time (s)	Control err. (m)	Max. speed (m/s)	Speed range (m/s)	Square err. (m·m·s)
Mean	19,11	0,00089	-0,17812	0,25811	0,16860
Median	18,30	-0,00011	-0,16316	0,22888	0,14475
Mode	#N/A	-0,00011	-0,16316	0,20848	#N/A
St. Deviation	6,22	0,00399	0,04729	0,08450	0,07868
Variance	38,64	0,00002	0,00224	0,00714	0,00619
Range	21,32	0,01370	0,16769	0,29006	0,32651
Minimum	10,00	-0,00359	-0,28100	0,16316	0,09764
Maximum	31,32	0,01010	-0,11331	0,45322	0,42415
Count	20	20	20	20	20

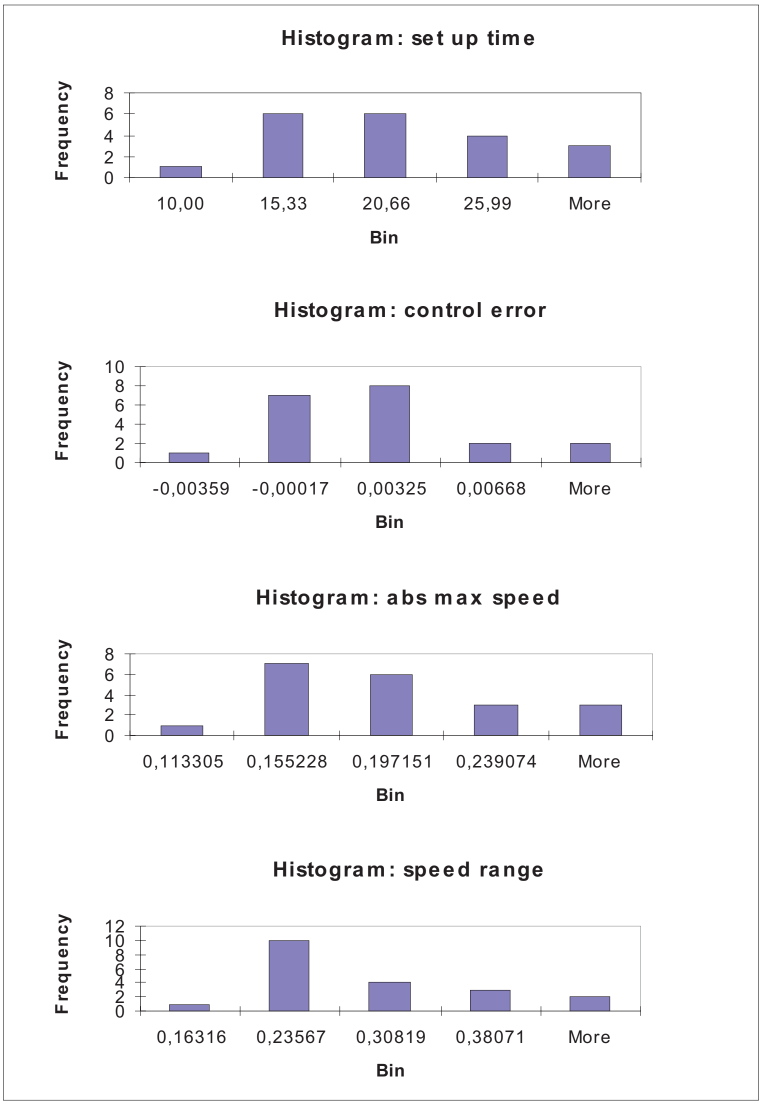

Figure 13: Histograms of the human control.

6 Conclusion

A comparison of statistically processed results of the set up time, control error, speed and speed range indicated that the results obtained with the developed controller are similar to the results of human control.

The results of the experiment verified that it is possible to develop a controller that uses qualitative representation of the plant. Results of automatic control were comparable to the results of human control of the discussed plant. We concluded that the designed intelligent controller achieved satisfied control properties on the balance control model!

Methodology we used for design and evaluation of the intelligent controller could be used for development of a controller for another plant. Formal validation is preferential: validation should occur within the development life cycle and identifies validation methods, input domain specifications, the level of acceptance and the relevant application of statistical techniques. Finally, we would like to lay emphasis on the next limitations. It is not recommendable to assess intelligent control using human control in every case. In some cases, we can not get the results of the human control. Also, it is possible that human control of the plant can not be a reference for intelligent controller verification because of its low performance in the discussed plant. In this instance, specification of the required performances can be used. Furthermore, field-testing is not always possible during the development cycle.

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