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Motion Control Demonstration for Easy Student Understanding*

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A combination of a selected teaching approach and content is presented in this paper that has succeeded repeatedly in capturing full attention of the entire class of professionally oriented mechatronics students to the problems of PID control, fuzzy logic control, and PID control with fuzzy adaptation. Students get absorbed in what otherwise they may perceive as a very dry and abstract material.

INTRODUCTION

AN IMPORTANT FEATURE of a successful mechatronic system is often the flexible combination of a simple mechanism and a sophisticated motion control [1]. The latter subject, however, in the author's Motion Control Design class was considered abstract and overly 'dry' material even though students of our Mechatronic Engineering program had already received credit for two Controls Principles courses.

The Motion Control Design course dwells on practical issues implied in the course's name, in the domain of both consumer products and machine building. Because PID (proportional integral differential) and fuzzy logic control are used extensively, in order to allow comparison, both are implemented on the same 'ball-on-beam experiment'. This is a rather well known motion control problem with a number of suppliers [2] providing the hardware as the test bed on which to develop and implement the required controls. (Other design courses in the curriculum train students how to design such hardware on their own.)

MOTION SYSTEM

The ball-on-beam motion system includes a grooved beam on which a steel ball can roll, Fig. 1. The beam tilt α depends on the motor shaft position θ. The groove of the beam is formed by two parallel rails. One is a wire-wound resistor with a fixed voltage applied to its terminals at either end of the beam. The other rail is a steel rod. As the ball rolls supported by both rails, it connects them electrically and acts like a wiper of the wire-wound potentiometer. Voltage from the steel rail provides feedback on the ball position along the track ('linear sensor' in Fig. 1).

SYSTEM DESIGN

The objective is to track position X of the ball along the beam to a commanded position by adjusting the beam tilt α in Fig. 1. This primary task is achieved by controlling the shaft position of a DC motor (as the secondary task) that delivers the appropriate angle θ for the required beam tilt α. The two angles are directly proportional for 'small' values of θ. The subdivision into two independent tasks or subsystems implied hereby is possible because the motor dynamics can be made to be much faster than the ball dynamics, meaning that the transients of the former are then not seen by the latter. Having subdivided the higher-order overall system into two simpler ones, the conventional wisdom would be to derive a mathematical model for both, and then to design a controller for each to satisfy respective design requirements specified in advance. These details are outlined in Appendix 1.

However, not only does this process of PID control synthesis assume a 'small' angle θ (for $\theta = \sin\theta$) despite the θ's 160° range (from −80° to +80°), but system parameters (particularly inertia reflected on the motor shaft) vary with the ball position. More importantly, vibrations of the beam and ball hopping on it are difficult to account for. In order to avoid (minimise) ball hopping, the actually calculated controller parameters had to be readjusted based on the engineering insight and intuition. It was then decided to build a fuzzy logic controller for the ball-beam subsystem that may be better suited to such insight and intuition. Details about this fuzzy logic controller are outlined in Appendix 2.

CLASS DEMONSTRATION

In essence, two separate algorithms, for PID and fuzzy logic control, are implemented on the same 'ball-on-beam' motion system. The author brings

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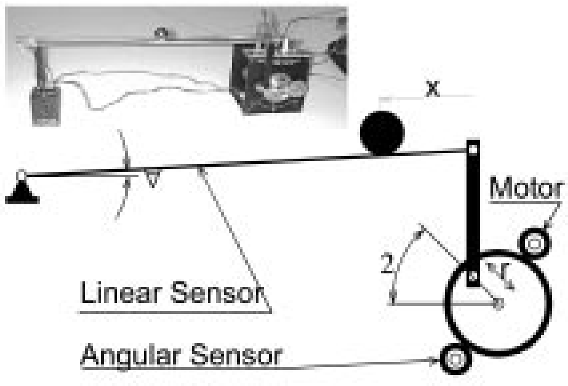

Fig. 1. System kinematics.

the actual hardware (and computer that executes the control routines and displays the input/output signals) to the classroom for class demonstration. A number of students are then invited to control the ball position manually by rotating the gear in Fig. 1 that affects the slope of the beam. This manual approach by a student volunteer is then named 'intelligent control'. Students quickly rename it 'unintelligent control' (or even worse) because no student has yet succeeded in stabilising the ball (students tend to perform as proportional 'P' controllers without the required differential 'D' action). Students who make the loudest or rudest remarks against their colleagues, are then invited to try their own skills. By realising their inability to make any headway, students gain respect for the subsequent quick and seemingly flawless performance by the PID control algorithm—no amount of talking could achieve the same effect. Weeks later, the merit of automation as being much more than merely a means of labour replacement, even if inexpensive labour force is abundant, sinks in far more easily.

After the wave of 'PID is good' excitement has calmed down, the author points to the students the undesirable aspects of the system performance. He also points to the difference between the controller parameters used and those predicted by calculations. They then jointly try to evaluate:

- how accurately they know 'constants' of the mathematical model;
- how inaccurate that model actually is despite its complexity;
- whether they had an alternative to the approxi mations introduced;
- how variable the system 'constants' are during the motion.

They actually set the controller parameters as determined by calculation and observe a very poor performance and phenomenon not included in the 'sound' model: ball hopping. They then discuss the merit of doing the seemingly precise modelling and PID system synthesis only to plug into it at the end quite rough estimates of the system constants and to adjust the final results based on engineering insight. While at this stage

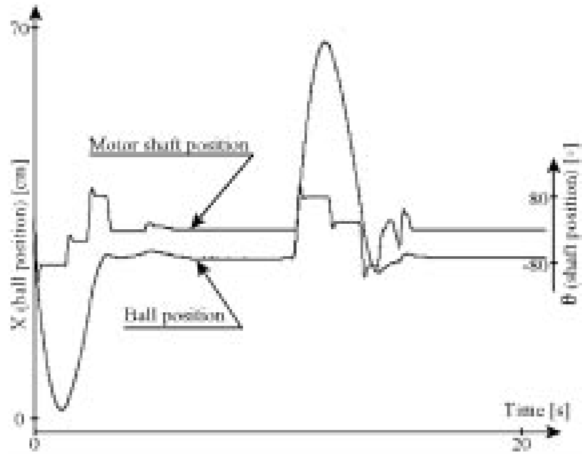

Fig. 2. Response with fuzzy controller.

PID control is still not considered 'bad', this has set a stage for the fuzzy control approach that starts with such engineering insight in the first place and does not maintain the notion of being very exact.

Another wave of excitement follows when fuzzy control is demonstrated on the same problem. As the ball goes quickly to the commanded position (Fig. 2), 'fuzzy is good' is heard. Once this second wave of excitement has calmed down, the author and his students try to identify what the key factors were in making the fuzzy approach work in this particular case and how this relatively complex problem was partitioned into simpler subsets (listed in Appendix 2). They then move to the negative aspects. The author brings to the students' attention the shimming under the leg of the table and where the need for the table to be horizontal came from—something not a problem for the PID algorithm. He points out that, while seemingly alike due to a dominant characteristic, each run is different, unpredictable and influenced by a single chance outcome. He reveals that the control is essentially limited to a set of conditions it

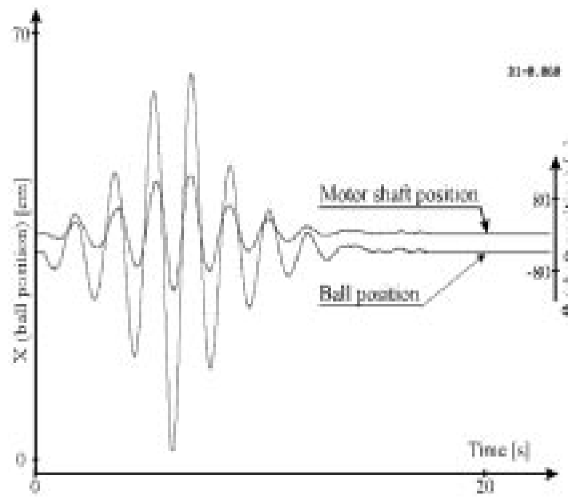

Fig. 3. Identifying optimal parameters for different stages of the transient response.

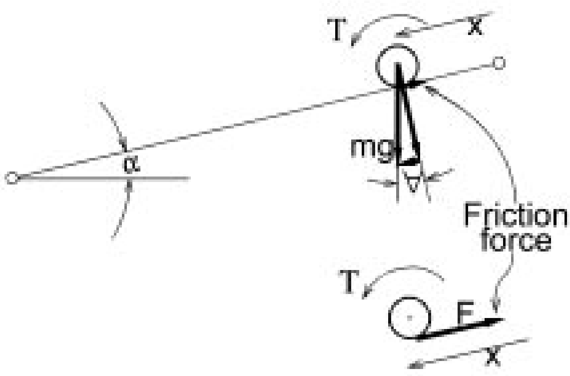

Fig. 4. Ball dynamics.

had been fine-tuned for, which is far more restrictive than what the PID could accommodate. They then go back to PID.

With PID running for the second time around, the author varies controller parameters on-line (as in Fig. 3) trying to identify the 'optimal' values for different stages of the ball transient on its way to the commended destination and for the steady state thereafter. While the traditional design wisdom would be to finally select a single value for each parameter and thereby strike a compromise between contradictory design requirements, they instead verbally articulate rules how those parameters should ideally vary during the process that they observe repeatedly. In essence, they formulate fuzzy rules, that bring them back to the fuzzy control, but this time fuzzy logic is used to adjust parameters of the PID controller on-line to suit each stage of the process—rather than to firmly fix them based on some compromise. As a result, with increasing ball position error, differential gain is altered first towards its calculated value and is then reduced gradually during the ball transient to obtain smooth, vibration-free performance in the steady state (Fig. 3) despite noisy feedback signals. Two 'hot keys' are enabled for this purpose for on-line controller parameter variation.

Monitoring of the effect of this variation is observed during different stages of the transient process of the ball motion. The observations made are:

- the differential gain should be set to the maximum permitted value of 0.25 (the manifestation of the beam vibration and ball hopping that are not included in the mathematical model impose this limit that is below the calculated value of 0.3);
- reduce it gradually with time at a suitable rate;
- set it to just above zero (0.02) for the steady state.

These observations are then expressed as fuzzy rules and form part of the fuzzy adapter that automates the PID controller's parameter adjustment. The author and his students conclude by realising that they made two full circles across PID and fuzzy control methods and ended up with a hybrid that combines useful features of both.

CONCLUSION

Mastering the PID control, fuzzy logic control, and PID control with fuzzy adaptation is undoubtedly important for professionally oriented students of Mechatronic Engineering. The teaching approach described in this paper has succeeded repeatedly in getting the students absorbed in this subject that they used to perceive as a very dry and abstract material. In essence, the author and his mechatronic engineering students of the Motion Control Design class implement the PID and fuzzy logic control on the same motion problem and hardware. They compare the performance of both methods repeatedly, appreciate the benefits of combining their useful features, and conclude that they ended up with a hybrid that combines useful features of them both: PID control with fuzzy adaptation. The final outcome is further

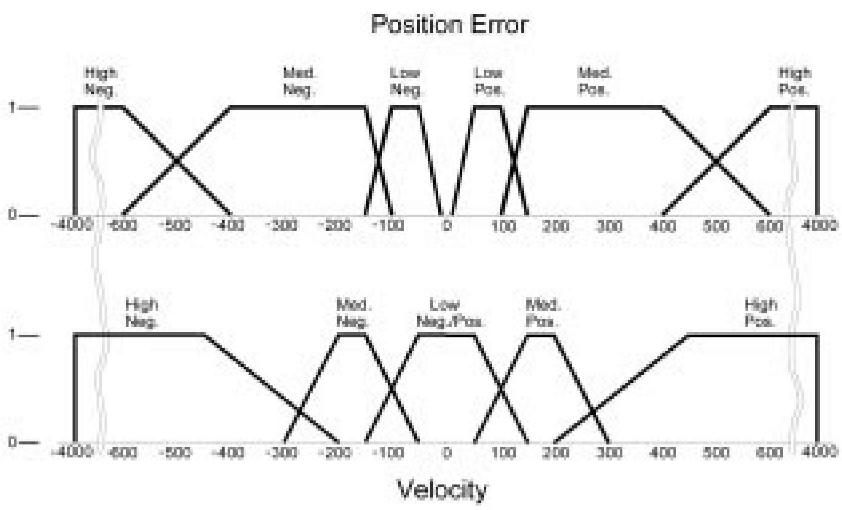

Fig. 5. Fuzzy partitions for position and velocity.

compared to the manual 'intelligent control' by a student volunteer whose inevitably disappointing performance leads the students to appreciate the merit of automation as being much more than merely a means of labour replacement—an issue of particular importance in regions surrounded by a relatively inexpensive labour force.

APPENDIX 1

PID control synthesis
The mathematical model is derived in three parts:

1. X $-$ α (ball position vs. beam tilt), for ball with mass m, moment of inertia J and radius R, Fig. 4:

$$mg\sin\alpha = m\ddot{x} + F$$
$$RF = \dot{\omega}J = \ddot{x}\frac{J}{R} \tag{1}$$

   Eliminating friction force F from these equations, for the ball moment of inertia $J = \frac{2}{3}mR^2$, after linearisation for small α, one gets: $\ddot{x} = \frac{5}{7}g\alpha$ and $X(s)/\alpha(s) = \frac{5}{7}(g/s^2)$.
2. $\alpha - \theta$ (beam tilt vs. motor shaft position). Approximation: rotation of the rod in Fig. 1 that connects the track and gear is neglected. In other words, this connecting rod is assumed to move as a rigid body, remaining vertical throughout the motion range. Then, $r\sin\theta = L\sin\alpha$ and, for small θ (although it is not small), $\theta = (L/r)\alpha$.
3. θ $-$ V (shaft position vs. supply voltage). The third part is the well known mathematical model of a (voltage controlled) permanent magnet DC motor (with $s(\tau s + 1)$ in the denominator of the transfer function). It is brought to the students' attention that the motor time constant τ depends not only on the inertia of the motor's rotor, but also on the inertia of the load reflected on the motor shaft. The latter inertia term varies strongly with the ball position. Consequently, as with most other mechatronic motion systems, this one is not with constant parameters.

Next, two PD controllers are designed. The output of one of them is the required angle α that is needed to affect the ball, and the other controller determines the output voltage for the motor so that the corresponding θ can be delivered. The P and D constants for two controllers, are (respectively): 0.312, 0299, 5.79 and 0.22 (for the design requirement of 0.707 for the damping factors and peak time of 3 s for the ball and 0.2 s for motor.

APPENDIX 2

Fuzzy logic control synthesis
Fuzzy rules used are of the form:

if
the ball is far to right (large positive position error),
and if
the high ball velocity is away from the desired destination (high positive velocity),
then
the beam should be inclined severely by raising its driven end significantly.

Velocity information is obtained by numeric differentiation of the position feedback.

A total of 36 such rules and input conditions have been identified for the ball velocity and position error as there are two fuzzy variables, ball position and velocity, with six partitions each (high, medium and small, positive and negative, with respect to the set point). Beam tilt is the output variable from the ball-beam fuzzy subsystem. It represents the input (set) point for the PID control of the motor dynamics that is to deliver the required beam-tilt based on the feedback from the sensor labelled 'angular sensor' in Fig. 1. As the PID motor-shaft position control is a routine task, only the ball-beam dynamics is discussed further.

It is apparent that the problem is anti-symmetric with respect to the zero position error point: changing the sign of both fuzzy variables (position and velocity) requires the exactly opposite beam tilt. Hence, only half of the fuzzy rules ($18 = 36/2$) had to be used explicitly: those for the position error positive were chosen. Any input condition with the negative position error was mapped into its counterpart with this error positive and with altered velocity direction, while flagging that the sign of the resulting beam tilt α must be altered subsequently.

A full list of the eighteen fuzzy rules is shown in Table 1.

Membership functions for the input variables and consequence levels were determined using intuition and test trials. A rough guide used in this process is summarised next:

1. The partition for 'low velocity' reflects total unreliability of the calculated velocity in the ± 50 region—fuzzy rules then do not utilise the motion direction information. Magnitudes above 50, with gradual increase in confidence, indicate the motion direction ('medium velocity').
2. The 'med.' and 'high' velocity partitions reflect the need for smoothness of the defuzzified command signal (output) with the gradual increase in velocity magnitude (the tilts are functions of the consequence levels).
3. For the 'small' and 'medium' position error, as well as the 'down low' and 'down low medium' consequence levels (Table 1), final settling of the ball was observed. Consequence number 9 (horizontal track) is used implicitly when none of the rules are called upon: fuzzification of the position error did not include its entire domain

Table 1. Fuzzy rules

Input condition			***Consequence*** (required output level) Required move for the driven end of the track
Index	Position error	Velocity	
1	High +	High +	Down Low Medium
2	High +	Med. +	Down Low Medium
3	High +	Low +	Down High
4	High +	Low −	Down High
5	High +	Med. −	Down High
6	High +	High −	Down High
7	Med. +	High +	Up High
8	Med. +	Med. +	Up Medium
9	Med. +	Low +	Down Low Medium
10	Med. +	Low −	Down Low Medium
11	Med. +	Med. −	Down High
12	Med. +	High −	Down High
13	Low +	High +	Up High
14	Low +	Med. +	Up Low Medium
15	Low +	Low +	Down Low
16	Low +	Low −	Down Low
17	Low +	Med. −	Down Medium
18	Low +	High −	Down High

as the region from −10 to +10 does not fall under any fuzzy partition. This region is further increased by the dead band of the drive system which does not respond to small inputs. The objective was to establish a zone within which the ball would stop by itself along the horizontal track when the ball enters this zone with the 'medium' velocity. The control continues only if the ball overshoots to the other end. This called for the 'med' velocity partition to be narrow around such ideal velocity for entering the zone (± velocity noise).

4. System dumping was studied for the 'med'/'big' position interface: by classifying the position error as 'big' sooner, more agile control is obtained.
5. It appears that the output state number 5 (up low) is not used since none of the 18 fuzzy rules calls for it. It should be noted, however, that this state is used with negative position error for input conditions corresponding to those positive ones that call for consequence 4 (down low). This is in connection with the switch from 36 to 18 rules as explained previously. An additional 'do nothing' output state is used implicitly when none of the other rules apply, as indicated by the deliberately built-in dead band apparent in the middle of the membership function for position-error in Fig. 3.

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Alexandar Djordjevich joined the faculty of City University of Hong Kong in 1992, where he is an Associate Professor in the Department of Manufacturing Engineering and Engineering Management. He was with the Research and Productivity Council of New Brunswick from 1989 to 1991 and Atlantic Nuclear Services from 1991 to 1992. His main research interests are focused on the application of structurally embedded fibre optic sensors and precision machining. He received the B.Sc. and M.Sc. degrees in Mechanical Engineering from the University of Belgrade in 1981 and 1985, respectively, and the Ph.D. degree from the University of New Brunswick in 1989 for his work on computer-controlled precision radiotherapy of patients with cancer.