PROPORTIONAL-INTEGRAL-PLUS (PIP) GAIN SCHEDULING CONTROL OF AN INTELLIGENT EXCAVATOR

Jun Gu, James Taylor and Derek Seward
Engineering Department, Lancaster University, Lancaster, LA1 4YR, UK
d.seward@lancaster.ac.uk

Abstract: This paper considers the design and implementation of an electro-hydraulic control system for a robotic excavator, namely the Lancaster University Computerised and Intelligent Excavator (LUCIE). The excavator is being developed to autonomously dig trenches without human intervention. Here, a gain scheduling design, based on Proportional-Integral-Plus (PIP) control methods, is utilised to regulate the highly nonlinear joint dynamics. Simulation and initial field tests both demonstrate the feasibility of the proposed technique, with the excavator arm directed along specified trajectories in a smooth, fast and accurate manner.

Keywords: robotic excavator; model-based control; gain scheduling control; proportional-integral-plus.

1. INTRODUCTION

The civil and construction industries currently deploy a large number of manually controlled plants for a wide variety of tasks within the construction process. The excavation of foundations, general earthworks and earth removal tasks are activities which involve the machine operator in a series of repetitive operations. Full or partial automation may improve excavation productivity, efficiency and operator safety, especially in applications such as underground mining or the removal of hazardous waste.

The Engineering Department at Lancaster University has a long record of research into autonomous excavation. In particular, the Lancaster University Computerized Intelligent Excavator (LUCIE) is based on a commercial manual hydraulic excavator (Fig. 1), but with an on-board computer system in place of a driver to control the hydraulics and therefore the machine [1-3].

The objective is to develop an intelligent excavator that can autonomously dig a trench in virgin ground without human intervention. Smooth, fast and accurate control of the excavator joints is an essential component of the system. In this regard, the present paper applies the Proportional-Integral-Plus (PIP) methodology to the joint control problem. Such PIP controllers can be interpreted as a logical extension of conventional PI/PID algorithms, but with inherent model-based predictive control action [4-5].

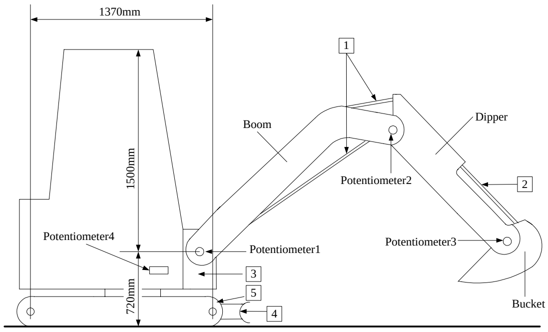


Figure 1. The LUCIE Excavator.

Here, Non-Minimal State Space (NMSS) models are formulated so that full state variable feedback control can be implemented directly from the measured input and output signals of the controlled process, without resorting to the design of a deterministic state reconstructor or a stochastic Kalman filter.

Over the last few years, such NMSS/PIP control systems have been successfully employed in a range of practical examples, including piling rig positioning [6] and LUCIE [3]. However, in the latter case, the nonlinear joint dynamics can sometimes yield an oscillatory response for bucket position. In order to maintain smooth control, therefore, previous control algorithms have typically utilised a relatively slow control action.

By contrast, the research described below develops a straightforward to implement, *gain scheduled* PIP control system, in order to increase the speed of response. Here, the differing joint dynamics when the digger arm is opening or closing, are accounted for by the design of separate PIP control algorithms in each case. The new approach is evaluated in both simulation and field tests.

2. THE EXCAVATOR

The tracked excavator used as the platform for the LUCIE project is a JCB 801 mini excavator, as illustrated in Fig. 1. The machine has an operating weight of 1.4 tons, is less than one meter wide, has a bucket capacity of approximately 940kg and a maximum vertical digging depth of about 1.5m.

It has been refitted with electro-hydraulic servo valves, associated sensors and a computer control system, to allow for the development, experimental evaluation and refinement of the new intelligent control systems.

All of the arm movements are hydraulically driven as follows (referring to the numbers in Fig. 1):

1. Movement of the arm in the (x, y) vertical plane uses two hydraulic cylinders that control the boom and dipper respectively.

2. Rotation of the bucket at the end of the dipper, in the same vertical plane, uses another cylinder.
3. Rotation of the cab at its connection to the undercarriage effectively provides movement for the arm in a horizontal plane (slew).
4. Movement up and down of a dozer blade at the front of the undercarriage.
5. Independent movement of two parallel caterpillar tracks for skid-steer movement of the whole platform.

The sensory equipment built into LUCIE is summarised below:

- Four potentiometers on the joints for angle measurement.
- A two-axis tilt sensor.
- A Leuze RotoScan RS 3 optical laser distance sensor for obstacle detection at a range of up to 15m.
- A Trimble 7400Msi series satellite GPS for location and navigation.

Finally, as illustrated by Fig. 2, LUCIE relies on three embedded PC 104 computers, each responsible for one of the three tasks listed below. The communication between these computers is provided by CAN-Bus (Controller Area Network).

- **High Level Controller (HLC)** is responsible for the planning of activities and navigation, such as which trench to dig first.
- **Low Level Controller (LLC)** is responsible for driving the valves and tracks by commands that are issued either by other processors or the joysticks. It also accepts inputs from the various potentiometers giving positional feedback. This component is the focus of the present paper.
- **Safety Manager (SM)** acts as the excavator conscience ensuring that the machine remains in a safe stable condition.

3. NMSS/ PIP CONTROL

Since there is little interaction between the dipper and boom hydraulics, the present research is based on the simplest multiple loop, single input, single output control algorithms, i.e. PIP controllers are designed for each joint separately.

In order to develop a linear PIP algorithm, a linearised representation of the system is first required. In this regard, the small perturbation behaviour of each joint is approximated by the following discrete-time transfer function,

$$y_k = \frac{b_1 z^{-1} + \cdots + b_m z^{-m}}{1 + a_1 z^{-1} + \cdots + a_n z^{-n}} u_k = \frac{B(z^{-1})}{A(z^{-1})} u_k \qquad (1)$$

where y_k is the joint angle (degrees) and u_k is the applied voltage, expressed as a percentage in the range -1000 to +1000. Positive and negative inputs open or close the joint respectively. Here, $A(z^{-1})$ and $B(z^{-1})$ are appropriately defined polynomials in the backward shift operator $z^{-i} y_k = y_{k-i}$.

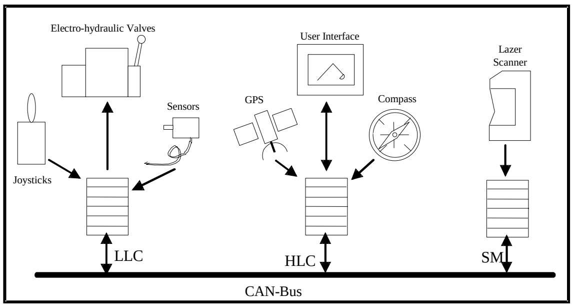


Figure 2. LUCIE Control System Architecture.

For convenience, any pure time delay of $\delta > 1$ samples can be accounted for by setting the $\delta - 1$ leading parameters of the $B(z^{-1})$ polynomial to zero.

The present research utilises the Simplified Refined Instrumental Variable (SRIV) algorithm to estimate the model parameters [7-8]. The model structure first needs to be identified, i.e. the most appropriate values for the triad [n, m, δ]. The two main statistical measures employed to help determine these values are the coefficient of determination R_T^2, based on the response error; and YIC (Young's Information Criterion), which provides a combined measure of model fit and parametric efficiency [7-8].

These statistical tools and associated estimation algorithms have been assembled as the CAPTAIN toolbox within the Matlab® software environment (www.es.lancs.ac.uk/cres/captain). The authors can be contacted for further details about this toolbox

It is easy to show that the model (1) can be represented by the following linear Non-Minimal State Space (NMSS) equations,

$$\begin{aligned} \mathbf{x}_k &= \mathbf{F}\mathbf{x}_{k-1} + \mathbf{g}u_{k-1} + \mathbf{d}y_{d,k} \\ y_k &= \mathbf{h}\mathbf{x}_k \end{aligned} \qquad (2)$$

where, **F**, **g**, **d** and **h** are defined by [3-6]. The *n*+*m* dimensional *non-minimal* state vector $\mathbf{x}_k$, consists of the present and past sampled values of the input and output variables, i.e.,

$$\mathbf{x}_k = \begin{bmatrix} y_k & y_{k-1} & \cdots & y_{k-n+1} \\ & u_{k-1} & \cdots & u_{k-m+1} & z_k \end{bmatrix}^T \qquad (3)$$

Here, $z_k = z_{k-1} + \{y_{d,k} - y_k\}$ is the *integral-of-error* between the reference or command input $y_{d,k}$ and the sampled output y_k. Inherent type 1 servo-mechanism performance is introduced by means of the *integral-of-error* state z_k. If the closed-loop system is stable, then this ensures that steady-state tracking of the command is inherent in the design.

The control law associated with the NMSS model (2) takes the usual State Variable Feedback (SVF) form,

$$u_k = -\mathbf{k}\boldsymbol{x}_k \qquad (4)$$

where $\mathbf{k} = [\, f_0 \; f_1 \cdots f_{n-1} \; g_1 \cdots g_{m-1} \; -K_I \,]$ is the SVF control gain vector. In more conventional block-diagram terms, the SVF controller (4) can be implemented as shown in Fig. 3.

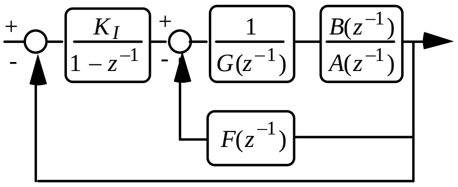


Figure 3. PIP control in feedback form.

It is clear from Fig. 3 that PIP control can be considered as one particular extension of the ubiquitous PI controller, where the PI action is, in general, enhanced by the higher order forward path and feedback compensators $1/G(z^{-1})$ and $F(z^{-1})$,

$$\begin{aligned} F(z^{-1}) &= f_0 + f_1 z^{-1} + \cdots + f_{n-1} z^{-(n-1)} \\ G(z^{-1}) &= 1 + g_1 z^{-1} + \cdots + g_{m-1} z^{-(m-1)} \end{aligned} \quad (5)$$

However, because it exploits fully the power of SVF within the NMSS setting, PIP control is inherently much more flexible and sophisticated, allowing for well-known SVF strategies such as closed loop pole assignment, with decoupling control in the multivariable case; or optimisation in terms of a conventional Linear-Quadratic (LQ) cost function, determined by the steady state solution of the ubiquitous discrete-time matrix Riccati equation.

Note that, in the NMSS/PIP case, the elements of the LQ weighting matrices have particularly simple interpretation, since the diagonal elements directly define weights assigned to the measured input and output variables.

4. GAIN SCHEDULING CONTROL

Gain scheduling is a powerful approach for the control of nonlinear and time-varying systems because of its simplicity and ability to use linear design methods [9]. The design of a gain scheduling controller involves the following steps [10],

1. Linearize the plant about a finite number of representative operating points.
2. Design linear controllers for the plant linearizations at each operating point.
3. Interpolate the parameters of the various linear controllers to achieve adequate performance of the linearized closed loop system at all points where the plant is expected to operate – the resulting family of linear controllers is the gain-scheduled controller.
4. Implement the gain scheduling controller on the nonlinear plant.

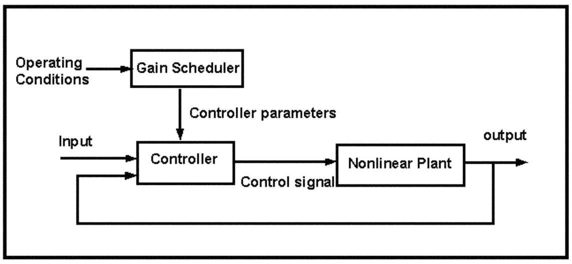


Figure 4. Gain-scheduled control.

The parameters of the gain scheduling controller evolve as functions of the plant states, inputs, outputs and exogenous parameters, or some combination of these. The gain-scheduled controller takes the general form illustrated by Fig. 4.

5. EXCAVATOR CONTROL

During automatic digging, the most important sub-target is to keep the bucket moving along a specified path quickly, smoothly and accurately. The straight line is the most common path employed, as in the case of dragging a flat bottomed trench in the ground, or moving the earth from the digging point to the dumping point. For high efficiency, such activities should be completed as quickly as possible.

Numerous researchers have considered this problem, with various degrees of success. For example, Nguyen [11] applies feedback linearization methods. In this case, experimental results indicate that the performance can be degraded by the presence of noise. Fuzzy moving sliding mode [12] and impedance [13] controllers have similarly been developed for robot excavators.

Budny [14] considers control of an excavator bucket in straight lines by applying Danfoss PVG 32 load-independent hydraulic valves. Here, the bucket was moved along planar vertical and horizontal lines in both free space and in a soil box filled with homogenous mildly humid sand. Although the accuracy is kept within 10cm, the velocity achieved was relatively low, only about 2m/min.

Similar tests for LUCIE, utilising conventional PI methods [1], also require slow movement of the bucket in order to maintain accurate control. This is the motivation for the development of a new PIP algorithm for regulating the joint dynamics [3]. The following section builds on this earlier research, by now developing a scheduled gain PIP control system for LUCIE and implementing further field tests.

6. CONTROL DESIGN FOR LUCIE

In order to identify the dominant dynamics of the excavator, joint data are collected for typical step changes in the applied voltage. In this case, the SRIV algorithm, combined with the YIC and R_T^2 identification criteria, suggest that a first order tranfer function model with either 1 or 2 samples time delay provides the best explanation of data across a wide range of operating conditions [3].

Furthermore, in common with many other hydraulic systems, such as [6], it is clear that both the boom and dipper angles behave as integrators, with an almost constant rate of change for a given input signal. For simplicity in the initial study, therefore, the following model structure is employed,

$$y(k) = \frac{bz^{-1}}{1-z^{-1}} u(k) \quad (6)$$

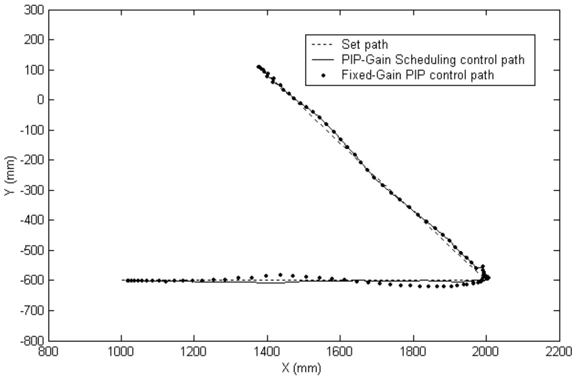


Figure 5. Simulation of bucket movement comparing fixed-gain PIP (dots), PIP-gain scheduling (solid) and the set path (dashed).

Here, $y(k)$ represents the boom or dipper joint angle, $u(k)$ is the associated input voltage and the numerator b is estimated using SRIV methods. A sampling rate of 0.1 seconds is utilised throughout, since this is within the capabilities of the on-line computer and is found to work well in practice.

Note that for all the analysis in the present paper, the dead-zone is removed at the data collection stage, so that a positive voltage scaled from 0 to 1000 causes the boom to open, whilst a negative voltage up to –1000 reverses the direction. In this manner, the boom can be positioned at an angle between 0 and 60 degrees, where the later figure represents fully open. Similarly, a scaled input voltage to the dipper in the range -1000 to 1000 causes the dipper angle to vary from -30 (fully open) to -140 degrees.

For example, a boom opening experiment with an input voltage of 60 yields the model (6) with $b = 0.005$. In this case, specifying closed loop poles at 0.6 on the real axis of the complex z-plane, yields robust PIP control of the boom angle when the latter follows an opening trajectory. Here, the PIP control gain vector is defined as follows,

$$\mathbf{K} = [128 \ \ -32] \tag{7}$$

By contrast, the PIP control algorithm for a decreasing boom angle, is based on a boom closing experiment with an input voltage of -40, which yields $b = 0.018$ and,

$$\mathbf{K} = [35.6 \ \ -8.9] \tag{8}$$

A similar approach is taken for the dipper angle. With an input voltage of –100 and 100 to open or close the joint, $b = -0.012$ and $b = -0.018$ respectively. The associated PIP gain vectors are given by,

$$\mathbf{K} = [-53.3 \ \ 13.3] \tag{9}$$

and

$$\mathbf{K} = [-35.6 \quad 8.9] \tag{10}$$

The above feedback gains (7) to (10) are utlised in the design of a scheduled control algorithm. Here, the key decision is how to choose appropriate control gains for each sampling period. In this regard, the controller utilizes a comparison between the current measured joint angle and the expected (commanded) angle of the arm at each sampling instant. For example, if the angle is larger than its expected value, the scheduler will choose the control parameters for the joint closing case.

For this particular implementation, interpolation between different operating points (for example using fuzzy methods) does not appear necessary. The inherent robustness of the basic PIP design over a range of operating levels ensures that the simple approach discussed here works very well, while the final design is particularly straightforward to implement in practice, as discussed below.

7. SIMULATION EXPERIMENTS

To demonstrate the behavior of the proposed control scheme, consider the simulation response shown in the polar coordinate plot of Fig. 5. Here, the simulation is based on a combination of excavator kinematics and data-based nonlinear dynamic models, implemented using the MATLAB/ SIMULINK© package, as described by reference [3].

The objective of this simulation experiment is to move the bucket from its initial position (1378, 109) to (2000, -600), and then to (1000, -600), where the (x, y) coordinates are given in mm from the point of attachment of the boom to the vehicle.

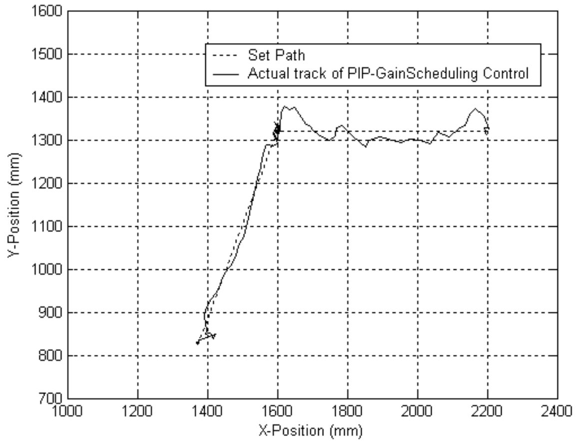
To avoid discontinuous force variations that may cause the arms to jerk during operation, the acceleration of the arms should be continuous. In this regard, the trajectory between each set of coordinates takes the form of a 5th order polynomial ‘jerk-free’ straight line as suggested by [15]. The objective is to complete the whole motion within 5 seconds, including a wait of 0.3 seconds at the initial position.

In Fig. 5, the bucket is moved along the defined straight-line trajectories well within the demanded time limitation. Compared with the fixed-gain PIP controller based on equations (8) and (10) only, the gain-scheduling algorithm provides more accurate and smoother performance. Although the latter difference is relatively small, these results presage the likely improvement of the approach when applied to the actual system, where any errors are multiplied.

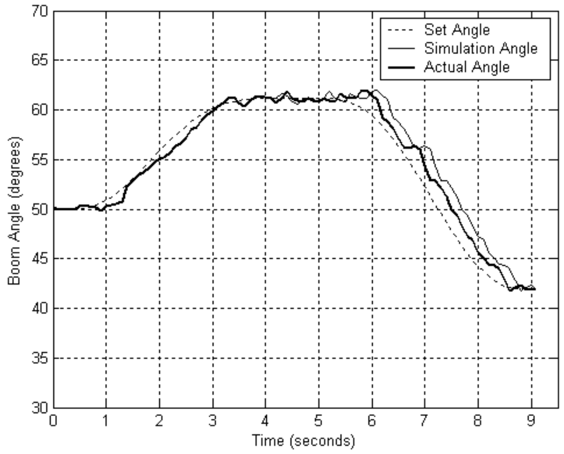
Although not shown in Fig. 5, both PIP algorithms provide considerably improved performance over a PID controller obtained using the Ziegler-Nichols ultimate sensitivity method. As discussed by [3], the latter algorithm only provides accurate control for relatively slow movements of the bucket.

8. FIELD EXPERIMENTS

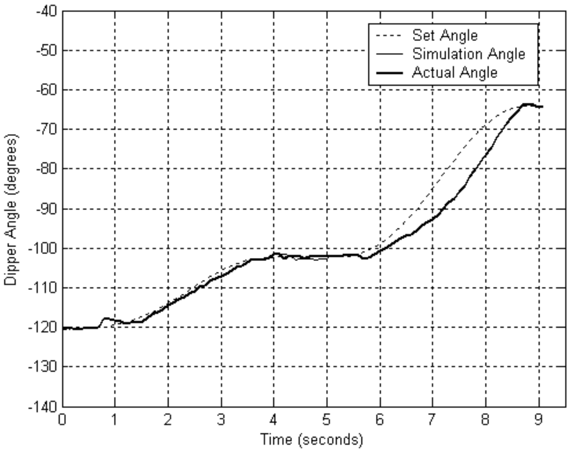
The test illustrated here is designed to move the bucket along a desired oblique straight line and a horizontal straight line. For safety reasons, all the bucket movements for these preliminary field tests are in air only.



(a) Bucket position.



(b) Boom angle.



(c) Dipper angle.

Figure 6. Implementation results, comparing the desired trajectory, the simulation response and LUCIE experimental data.

A Turbo C++ programme was written by the 1st author and executed under the DOS 6.0 operating system, to realize the PIP-gain scheduling control algorithm. During the experiment, the hydraulic pressure is kept at 1.1×10^{7} Pa.

Fig. 6 (a) shows the bucket moving from its initial position at (1368, 829) to (1600, 1320) along an oblique straight line in 4 seconds. Following a programmed 1 second delay, the bucket moves to (2200, 1320) along a horizontal straight line in a further 4 seconds. As before, the (x, y) coordinates are given in mm from the reference point.

As expected, the bucket moves closely along the reference path with an error magnitude less than 20mm during the oblique straight line motion. When the bucket moves along the horizontal straight line, the error magnitude is maintained lower than 50mm.

Since the bucket position is decided by the angle of boom and dipper according to the kinematic relationship of joints established by [2], the key to the proposed bucket position control depends on the respective boom and dipper angle controllers. In this regard, Fig. 6 (b) and (c) show the tracking responses of the boom and dipper respectively. In these figures, the actual angles of the boom and dipper closely follow the equivalent simulated values, attesting to the accuracy of the previously developed nonlinear simulation model [3], as well as the associated linear transfer functions utilised for control system design.

However, it is clear from Fig. 7 (b) that there is some vibration when the boom tracks the desired angle. Although this vibration is less than 1.5 degrees, it yields a noticeable positional error in bucket position because of the long transmission length of over 1.5m. This is the main factor that leads to bucket position errors. Most commonly, such vibration occurs when: (i) the boom changes its direction of motion, e.g. from opening to closing; (ii) any movement from stationary; or (iii) big changes of drive-demand even if they are in the same direction.

Another factor that can partially explain the position errors are delayed responses from the hydraulic system, i.e. the response time of the hydraulic system sometimes lags behind the real time requirements. In particular, longer pure time delays than the unity implied by equation (6) sometimes occur. For this reason, the authors are presently considering PIP controllers based on models with longer time delays. In fact, one of the key advantages of PIP control over conventional PI/PID design, is that the former approach robustly accommodates such long pure time delays [3-4].

9. CONCLUSIONS

In moving towards autonomous excavation for a heavy hydraulic excavator, fast and smooth bucket position control is an essential step. However, this requirement presents a difficult control problem because of the nonlinear excavator dynamics.

The present paper follows up earlier research into Proportional-Integral-Plus (PIP) control of the Lancaster University Computerized Intelligent Excavator or LUCIE [3], by now developing a gain scheduled system. Here, appropriate PIP control gains are chosen at each sampling instant, based on the current operating state of the excavator arm.

Unmodelled dynamic effects such as vibrations of the boom, together with occasional large time delays, both influence the tracking performance of the bucket position controller. Nonetheless the results obtained in both simulation and preliminary field tests are very promising. They show that the PIP-gain scheduling control system is able to drive the bucket along desired trajectories, with an accuracy and speed considerably higher than previously obtained.

In particular, the accuracy is within 50mm, while the velocity reaches 9 meters per minute. These are within the requirements of normal excavation tasks. In fact, the new control system offers performance that is comparable to that achieved by an average human operator.

The scheduler utlised to date is very straightforward: the parameters are divided into two groups based on whether the arm is opening or closing. However, the authors are presently considering more sophisticated approaches to the scheduling. For example, one solution is to divide the parameters into groups based on the different velocity requirements.

Another novel research area currently being investigated at Lancaster, in order to improve PIP control in the case of nonlinear systems, is based on the State Dependent Parameter (SDP) system identification methodology. Here, the nonlinear system is modelled using a quasi-linear model structure in which the parameters vary as functions of the state variables [16]. Preliminary simulation studies have demonstrated the utility of such models in the design of SDP-PIP control systems [17].

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REFERENCES

[1] Seward, D. and Quayle, S, “LUCIE - Lancaster University Computerised Intelligent Excavator”, *Circ. Cellar: Comput. Appl. J.*, 79, pp. 67-73, 1997.

[2] Bradley, D.A. and Seward, D.W., “The Development, Control and Operation of an Autonomous Robotic Excavator”, *J. of Intelligent and Robotic Systems*, Vol. 21, pp. 73-97, 1998.

[3] Gu, J., Taylor, C.J. and Seward, D., “Proportional-Integral-Plus Control of an Intelligent Excavator.” *J. of Computer-Aided Civil and Infrastructure Engineering*, Vol. 19, pp. 16-27, 2004

[4] Young, P.C., Behzadi, M.A., Wang, C.L. and Chotai, A., “Direct Digital and Adaptive Control by Input-Output, State Variable Feedback Pole Assignment”, *Int. J. of Control*, Vol. 46, pp. 1861-1881, 1987.

[5] Taylor, C. J., Chotai, A. and Young, P. C., “State space control system design based on non-minimal state-variable feedback; Further generalisation and unification results”, *Int. J. of Control*, Vol. 73, pp. 1329-1345, 2000.

[6] Dixon, R., Chotai, A., Young, P.C. and Scott, J.N., “ The Automation of Piling Rig Positioning Utilising Multivariable Proportional-Integral-Plus (PIP) Control”, *Proc. 12th Int. Conf. on Systems Engineering, ICSE’97*, Coventry University, UK, 9-11 September, 1997.

[7] Young, P.C., “Recursive Estimation and Time Series Analysis”, *Communication and Control Engineering Series*, Springer-Verlag, Berlin, 1984.

[8] Young, P.C., “Simplified Refined Instrumental Variable (SRIV) estimation and True Digital Control (TDC): a tutorial introduction”, *Proceedings of the First European Control Conference*, Grenoble, 1991.

[9] Murray-Smith, R. and Johansen, T. A., (Eds.), “Multiple Model Approaches to Modelling and Control”, Taylor & Francis, 1997.

[10] Kaminer, I., Pascoal, A. M., Khargonekar, P. P., and Coleman, E. E., “A Velocity Algorithm for the Implementation of Gain-Scheduled Controllers”, *Automatica*, Vol. 31, No. 8, pp. 1185-1191, 1995.

[11] Nguyen, Q., Ha, Q., Rye, D. and Durrant-Whyte, H., “Feedback linearization control of electro hydraulic systems of a robotic excavator”, *Proc. Australian Conference on Robotics and Automation*, Brisbane, pp. 190-195, 1999.

[12] Ha, Q., Rye, D. and Durrant-Whyte, H, “Fuzzy moving sliding mode control with application to robotic manipulators”, *Automatica*, Vol. 35 (4), pp. 607-616, 1999.

[13] Ha, Q., Nguyen, Q., Rye, D. and Durrant-Whyte, H., “Impedance control of a hydraulic actuated robotic excavator”, *Journal of Automation in Construction*, 2000.

[14] Budny, E., Chlosta, M. and Gutkowski, W., “Load-independent control of a hydraulic excavator”, *J. of Automation in Construction*, Vol. 12, pp. 245-254, 2003.

[15] Chiang, M-H. and Murrenhoff, H., “Adaptive servo-control for hydraulic excavators”, *Power Transmission and Motion Control, PTMC’98*, Professional Engineering Publishing Limited London and Bury St Edmunds, UK, pp. 81-95, 1998.

[16] Young, P.C., “Stochastic, Dynamic Modelling and Signal Processing: Time Variable and State Dependent Parameter Estimation”, *Nonlinear and nonstationary signal processing*, edited by W. J. Fitzgerald *et al.*, Cambridge University Press, Cambridge, pp. 74-114, 2000

[17] McCabe, A.P., Young, P., Chotai, A. and Taylor, C.J., Systems Science (Warszawa, Poland), Vol. 26, pp. 25-46, 2000.