CONTROL OF NONLINEAR SYSTEMS IDENTIFIED USING SCHEDULED, ADAPTIVE AND STATE DEPENDENT PARAMETER MODELS

Final Report for EPSRC Grant Reference GR/R94442/01

James Taylor and Matthew Stables, Engineering Department, Lancaster University, LA1 4YR

1. BACKGROUND

Although nonlinear systems occur extensively in the field of dynamic analysis, their control presents the designer with a difficult challenge. Exact linearisation by feedback provides one approach [1], while partially linear techniques include gain-scheduling, velocity-based linearisation [2] and bilinear systems control [3]. It is clear from such examples that a common strategy involves attempting to bring the original system into a quasi-linear domain, before subsequently designing an appropriate linear control algorithm. Indeed, for many nonlinear systems, the essential small perturbation behaviour can be approximated by linearised transfer function models. This is the approach previously employed for *Proportional-Integral-Plus* (PIP) control system design. 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 resort to the design and implementation of a state reconstructor or Kalman filter [4-5].

This three year project has utilised the generic NMSS / PIP framework in a comparative evaluation of several well known approaches to control systems design. These include: controllers based on linearization about an operating point; scheduled control; adaptive control; and exact linearization by feedback; together with a recently suggested method based on the identification of *State Dependent Parameter* (SDP) models. In the latter case, the nonlinear system is modelled using a quasi-linear structure in which the parameters vary as functions of the state variables [6]. The project has focused on two very different application areas, namely control of the built environmental and construction robots. The main achievements are:

1. Development of fully operational NMSS / PIP control systems for the following applications:
    - Automation of a vibro-lance system used for ground improvement on a construction site, based on a commercial hydraulic excavator. Field tests with industrial partner Bachy Soletanche Ltd.
    - Automatic trench digging using both the Lancaster University Computerised Intelligent Excavator (LUCIE) and a closely related 1/5th scale laboratory representation in a sandpit.
    - Control of micro-climate in environmental test chambers representing sections of a livestock building or glasshouse, at both Lancaster University and Katholieke Universiteit Leuven.
    - Participation in the ALSTOM Benchmark Challenge II – multivariable gasifier simulation.
2. Utilization of these four examples in a comparative evaluation of a wide range of approaches to nonlinear control. Implementation results for the practical applications suggest that, in cases with a high degree of nonlinearity, the novel SDP-based methods typically yield the most robust, accurate control.
3. Following referees comments highlighting an unrealistic work-load, the research objective relating to the development of NMSS methods for input and output constraints was given a relatively low priority. Nonetheless, the project has recently utilized a model-predictive control framework to develop NMSS-based control systems that inherently allow for the specification of hard and soft constraints.
4. Development of NMSS / PIP methods for the control of a widely applicable class of nonlinear systems, based on the identification of appropriate SDP models, with successful practical demonstrators as above.

In fact, all the research objectives of the initial proposal have been successfully completed on schedule. The only revision to the work-plan was the enforced replacement of the robot arm *Starlifter* with two new robot arm examples (see section 4).

2. METHODOLOGICAL ADVANCES

Although the focus of the original research proposal was the development of the practical demonstrators, one key methodological advance has been the theoretical development and subsequent exploitation of SDP-based control systems, i.e. objective 4 in the list above. In this regard, consider the following nonlinear model,

$$y_k = \mathbf{w}_k^T \mathbf{p}_k \quad ; \quad \mathbf{w}_k^T = [-y_{k-1} \;\; -y_{k-2} \;\; \cdots \;\; -y_{k-n} \;\; u_{k-\tau} \;\; \cdots \;\; -u_{k-m-\tau+1}] \tag{1}$$

$$\mathbf{p}_k = [a_1\{\boldsymbol{\chi}_k\} \;\; a_2\{\boldsymbol{\chi}_k\} \ldots a_n\{\boldsymbol{\chi}_k\} \;\; b_\tau\{\boldsymbol{\chi}_k\} \ldots b_{\tau+m-1}\{\boldsymbol{\chi}_k\}]^T \;\; ; \;\; \boldsymbol{\chi}_k^T = [\mathbf{w}_k^T \;\; \mathbf{U}_k^T] \;\; ; \;\; \mathbf{U}_k = [U_{1,k} \ldots U_{r,k}]$$

where y_k and u_k are the output and control input variables respectively, while $a_i\{\boldsymbol{\chi}_k\}\,(i=1,2,\ldots,n)$ and $b_j\{\boldsymbol{\chi}_k\}\,(j=\tau,\tau+1,\ldots,m+\tau-1)$ are the state dependent parameters [6]. The latter are assumed to be functions of a state vector $\boldsymbol{\chi}_k$, in which $\mathbf{U}_k$ is a vector of *r* external variables. Finally, $\tau \geq 1$ is the pure time (transport) delay of the system. The linear-like, affine structure of the SDP model means that, at each sampling instant, it can be considered as a non-minimal state space 'frozen' linear system as follows,

$$\mathbf{x}_k = \mathbf{F}(\boldsymbol{\chi}_k)\mathbf{x}_{k-1} + \mathbf{g}(\boldsymbol{\chi}_k)u_{k-1} + \mathbf{d}y_{d,k} \;\; ; \;\; y_k = \mathbf{h}\mathbf{x}_k \;\; ; \;\; \mathbf{x}_k = [y_k \;\; y_{k-1} \cdots y_{k-n+1} \;\; u_{k-1} \cdots u_{k-m+1} \;\; z_k]^T \tag{2}$$

where the non-minimal state vector $\mathbf{x}_k$ consists of the sampled input and output variables, together with an *integral-of-error* state variable introduced to ensure inherent type 1 servomechanism performance, i.e. $z_k = z_{k-1} + \{y_{d,k} - y_k\}$ where $y_{d,k}$ is the command level. For brevity, the state transition matrix $\mathbf{F}(\boldsymbol{\chi}_k)$, together with $\mathbf{g}(\boldsymbol{\chi}_k)$, $\mathbf{d}$ and $\mathbf{h}$ are omitted here, but the closely-related linear equivalents are given by numerous earlier publications, e.g. [4-5]. This formulation is coupled with linear system design strategies such as pole assignment or suboptimal Linear Quadratic (LQ) design. The approach yields SDP-PIP control systems in which the state feedback gains are themselves state dependent, i.e. $u_k = -\mathbf{k}_k \mathbf{x}_k$ where the control gain vector $\mathbf{k}_k$ is obtained recursively at each sample. For basic SDP control system design, it is usually sufficient to limit the model (1) to the case that $\boldsymbol{\chi}_k = \mathbf{w}_k$. In fact, many nonlinear systems can be described by a further subset of the entire class of SDP models, represented by the following difference equation,

$$y_k = -a_1\{\boldsymbol{\chi}_k\}y_{k-1} - a_2\{\boldsymbol{\chi}_k\}y_{k-2} \dots - a_n\{\boldsymbol{\chi}_k\}y_{k-n} + b_1\{\boldsymbol{\chi}_k\}u_{k-1} \tag{3}$$

Here, the input component of the model is limited to a single element $b_1\{\boldsymbol{\chi}_k\}u_{k-1}$. The present research shows that the response of the SDP-PIP system derived from equation (3), exactly equals the 'designed-for' linear response, such as the dead-beat solution, assuming only that the *linear controllability conditions are satisfied at each sample*. In other words, the SDP-PIP gains are updated at each sampling instant, so that the closed-loop response equals that of a linear open-loop system with the same (assigned) poles. Although this analytical result assumes zero model mismatch, the robustness of the approach is illustrated by the practical demonstrators considered below. For the model (3), the controllability conditions reduce to $b_1\{\boldsymbol{\chi}_k\} \neq 0, \forall k$. This special case is chosen because, in the case of *nonlinear* systems, the influence of numerator terms and/or pure time delays is rather complex and may lead to an undesirable, even unstable response [9]. However, research for this project has focused on two potential solutions:

In the first instance, for the general SDP model (1), recourse is made to a 'partial linearisation by feedback' approach to handle the higher order input terms, motivated by limitations in conventional exact linearization via feedback. In particular, simulation studies suggest that the robustness of the latter approach is relatively poor in the SDP case. However, by linearising only the 'input' terms of the system and utilising the SDP-PIP feedback algorithm to handle the 'output' terms, nonlinear models described by equation (1) become fully controllable by nonlinear pole assignment or LQ design [18-19]. Secondly, a Smith Predictor-based solution has been developed for the commonly encountered scenario that the subset model (3) has a time delay greater than unity. In this case, a discrete-time Smith Predictor is utilized to ensure that the delay is external to the control loop, as shown in Fig. 1. Here, the feedback polynomial $F_k(z^{-1}) = f_{0,k} + f_{1,k}z^{-1} + \cdots + f_{n,k}z^{-n}$ and the system model are both represented in terms of the backward shift operator, i.e. $z^{-i}y_k = y_{k-i}$, while circumflexes indicate estimated values and, finally, $k_{I,k}$ is the integral gain.

The right hand subplot of Fig. 1 compares linear PIP designed for 300m^3/hour with an equivalent SDP-PIP algorithm, when both are applied to a nonlinear model of ventilation rate and pole assignment methods are utilized to specify a particular speed of response. The open-loop response for these poles is exactly equal to the SDP-PIP case *even during the transition between operating levels* whilst the linear algorithm deviates when the output falls away from 300m^3/hour. Although for brevity Monte Carlo simulations are not shown here, the study further demonstrates that the new approach maintains as good or better robustness properties and improved disturbance rejection, in comparison to linear or scheduled control alternatives [9]. As discussed below, the latter point is of particular importance in the context of environmental control. Finally, for faster pole positions (such as dead-beat) only the SDP-PIP algorithm guarantees stability.

Finally, with regards to objective 3 above, the project has employed an approach to hard and soft constraints that exploits the advantages of the special NMSS structure within the context of model predictive control. Here, the NMSS-based algorithm is solved using a scheme in which the control signal is optimized in real-time in order to achieve optimality, subject to plant operational constraints. Recent research by the PI and collaborators has extended these results to allow for an alternative NMSS model predictive control structure with potential robustness and disturbance rejection advantages in practice [7-8].

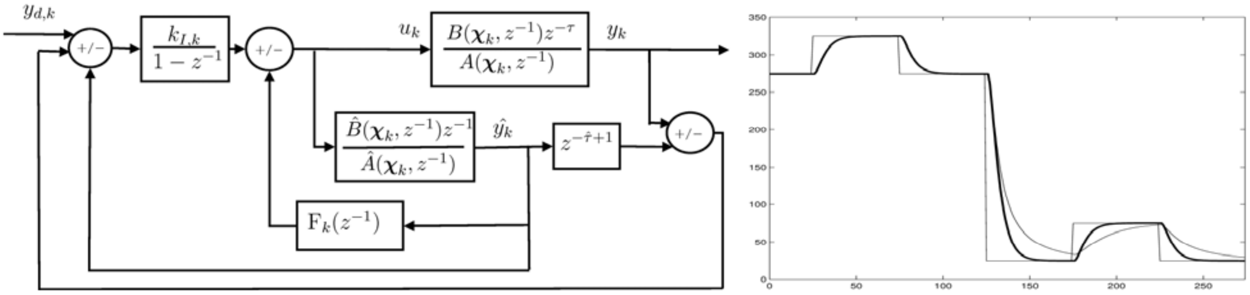

Fig. 1 SDP-PIP control with Smith Predictor; response of nonlinear ventilation rate model for various command steps, comparing linear PIP (thin trace) and SDP-PIP (thick trace), where the latter is exactly equal to the design response.

3. PRACTICAL DEMONSTRATORS

The primary objective of the project was to utilize both real and simulated examples to evaluate the various control technologies discussed above. These results are summarized below.

Automated verticality alignment system for a vibro-lance

The civil and construction industries currently deploy a large number of manually controlled plants for a wide variety of tasks within the construction process, utilising a range of heavy hydraulic machinery including cranes, excavators, piling rigs and graders. Semi-automatic functions are starting to be adopted as a means of improving efficiency, quality and safety. However, a persistent stumbling block for developers is the achievement of adequate movement under automatic control. The behaviour of hydraulically driven manipulators is dominated by the highly nonlinear, lightly damped dynamics of the actuators. The problem is generally made more difficult by a range of factors that include highly varying loads, speeds and geometries.

The present project has considered the automation of a vibro-lance used for ground improvement on a construction site, supported by an industrial partnership with Bachy Soletanche Ltd. Here, a vibrating probe is lowered into the ground and penetrates downwards by means of a two arm excavator, compacting the surrounding soil, as illustrated in Fig. 2. For the present study, liquid-based inclinometers, fitted with integrated electronics, measure the absolute angle of each joint. They are straightforward to install and do not require any alternations to be made to the excavator. Similarly, rather than replace the existing hydraulic valve actuators, it proved more economical and practical to incorporate additional control valves and hydraulic circuitry in parallel with the conventional proportional hydraulic controller [11].

The automatic control task is to maintain the verticality of the probe. Inverse kinematics are utilised on-line to convert this task into a desired trajectory in the joint space, whilst a PIP controller maintains the specified joint angles. When lowering the arm, errors may result in the void being off-set from the vertical, while raising the arm is a particularly critical stage, since the probe may be damaged if it deviates too far. However, linear PIP design yields an error between the tool-tip trajectory and the horizontal set point of less than 10cm for over 90% of the time and, apart from the initialization period, is never more than 17cm, well within the 30cm required to avoid damage, as illustrated by Fig. 2 [11]. Subsequent research looking at scheduled, adaptive and SDP-based approaches indicate that the nonlinearities in the system, thought to be responsible for the initialization problems, can be best represented by using the following SDP models,

$$y_k = a_1 y_{k-1} + b_2\{\chi_k\} u_{k-2} \quad ; \quad \begin{array}{ll} b_2\{\chi_k\} = -7.63\times10^{-6}\, u_{k-2} + 0.0066 & \text{(joint 2 - boom arm)} \\ b_2\{\chi_k\} = -1.078\times10^{-5}\, \left|u_{k-2}\right| + 0.015 & \text{(joint 3 - dipper arm)} \end{array} \tag{4}$$

Here, y_k represents joint angle 2 or 3 and u_k is the applied voltage. Note that SDP analysis of experimental data indicates that $b_2\{\chi_k\}$ is a function of the lagged input variable in both cases, while $a_1 = -1$ is time invariant. In fact, $a_1 = -1$ is fixed while obtaining the final estimates of $b_2\{\chi_k\}$ in order to simplify the analysis. The associated SDP-PIP algorithm has been evaluated for movement of the vibro-lance in both air and in soil, the latter experiments taking place at construction sites in Leeds and Liverpool. These results show that the SDP-PIP approach increases the speed of operation by a factor of three in comparison to manual control, whilst also yielding improved accuracy over linear design and, therefore, a potential increase in tool life [11]. Video footage is available for download at: www.lancs.ac.uk/staff/taylorcj/nonlinear.

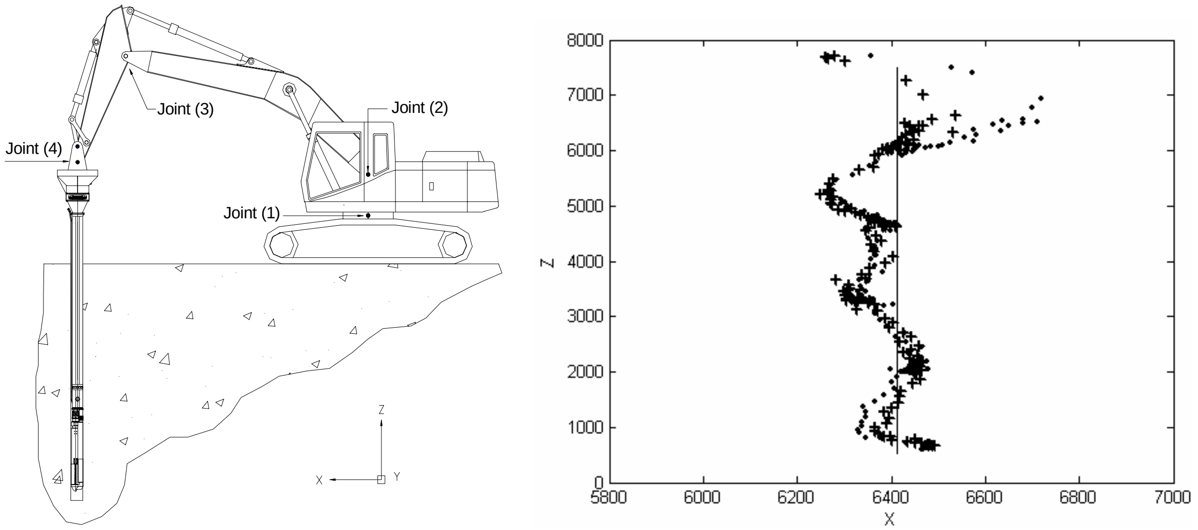

Fig. 2 Hydraulic two-arm manipulator with vibro-lance (left); implementation experiment with the resolved position of the end-effector (mm), showing both linear (dots) and nonlinear (crosses) control, together with the horizontal set point.

Laboratory and field demonstration of automatic trench digging

The four degree of freedom digger arms considered here include both the Lancaster University Computerised Intelligent Excavator (LUCIE), which is being developed to dig foundation trenches on a building site [16], and a 1/5th scale laboratory representation of LUCIE, used to develop new control methodologies in a sand-pit [18]. The new control system includes high-level commands for positioning of the bucket, digging and the removal of soil, coupled with low-level PIP control of each joint. Although a straightforward scheduled PIP approach [22] yields smoother, more accurate movement of the bucket position in comparison to linear designs, the full SDP-PIP algorithm provides the best compromise between performance and robustness. In particular, whilst the dipper movements are adequately approximated by linear transfer function models [16], the boom dynamics are sufficiently nonlinear that the additional complexity of the SDP approach proves worthwhile. Here, the SDP model takes the form of equation (1) and, hence, recourse is made to the novel partial linearization by feedback approach mentioned above [19-20].

Regulation of microclimate in environmental test chambers

The project has contributed to the development of a $1m^2$ by 2m forced ventilation test chamber at Lancaster University [13]. Here, an axial fan positioned at the outlet draws air through the chamber, whilst the inlet airflow is independently regulated by a second fan used to represent realistic pressure disturbances (Fig. 3). Specifications are completed by an array of thermocouples and a heater. The chamber has been utilized for research and training by post-graduate students in various disciplines. For example, it has been used to cross-calibrate anemometers; to develop new passive air samplers; and to examine the bio-response of a habitant. However, the focus of the present project has been ventilation rate control. This is one of the most significant inputs in the control of microclimate within agricultural buildings. Here, nonlinearities include the s-shaped steady state relationship between applied voltage and ventilation rate; and the fact that at low applied voltages, or for certain realistic pressure disturbances, the airflow patterns do not necessarily stabilize.

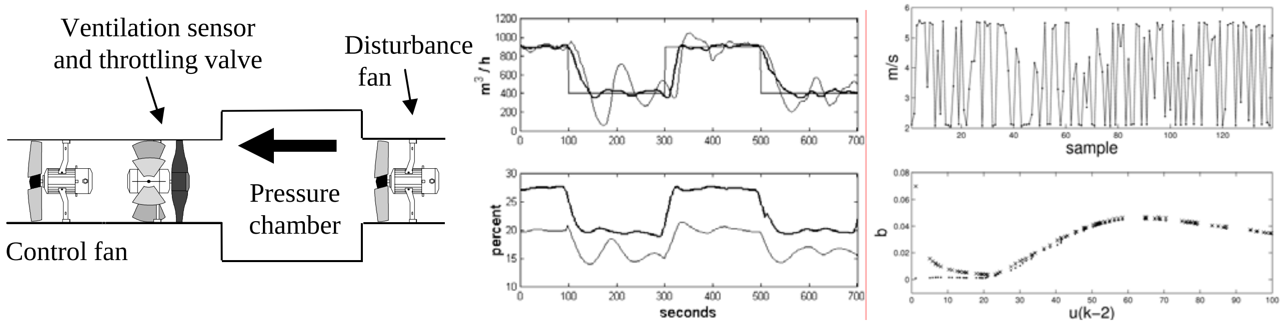

Fig. 3 Left: test chamber schematic diagram. Middle: comparison of scheduled gain (thick trace) and linear PIP control, showing the ventilation rate (top graph) and applied voltage. Right: measured airflow data (dots) and identified SDP model response plotted against sample number (top graph); and the SDP $b_2\{\chi_k\}$ plotted against u_{k-2}.

It is obvious that a scheduled approach will yield improved performance over linear fixed gain control, as illustrated by the middle subplot of Fig. 3. Here, a throttling valve is activated at low ventilation rates to help stabilize the airflow by generating higher static pressure differences over the fan, but hence requiring a second set of control gains [17]. For the fully nonlinear approach, based on SDP models, a multivariable identification problem emerges, which was solved in the project by the introduction of 'dummy' state variables [21]. In this regard, the right hand subplot of Fig. 3 shows the identified shape of the state dependence for a typical open-loop experiment. As would be expected from the discussion in section 2, implementation results confirm that only the SDP-PIP with Smith Predictor approach always yields the correct design response [9], whilst it has the further advantage of improved disturbance rejection properties in comparison to linear, scheduled and adaptive control.

Finally, environmental test chambers at the Katholieke Universiteit Leuven have been used to support the research and to develop an improved throttling valve algorithm. In this case, the throttling valve is directly employed as a second control actuator, utilising airflow from either the axial fan or potentially from natural ventilation. This new combined fan/valve configuration was compared with a commercial PID controller and a scheduled PIP design, yielding a reduction in power consumption of up to 45% in both cases [14].

ALSTOM Benchmark Challenge II – multivariable nonlinear gasifier simulation

This simulation includes all the significant physical effects related to the gasification system of an integrated gasification combined cycle power plant; e.g. drying processes, desulphurization and pyrolysis. It has previously been validated against measured time histories from a British Coal experimental test facility. In essence, the benchmark is a nonlinear, multivariable simulation based on four highly constrained controllable inputs, i.e. a linked coal and limestone variable, air, steam and char extraction, together with a pressure disturbance and various boundary conditions, including a coal quality parameter. The pressure, temperature, bed-mass and gas quality must all be maintained within specified limits, despite the effects of the disturbance signal. In the first instance, a linear NMSS / PIP control algorithm was developed. The approach was based on the identification of discrete-time transfer function models utilising a very straightforward design process, requiring one open-loop experiment and automatic selection of linear models based on statistical criteria. Manual tuning of the weighting parameters yields a linear PIP design that successfully satisfies *all* the benchmark objectives without violating the input constraints [12]. These results apply at all the specified operating conditions, pressure disturbances and for coal quality disturbances of up to 8%, comparable with other, typically more computationally intensive, approaches also considered at the special session of *UKACC Control*, September 2004, Bath, UK.

Small improvements in performance are possible using the scheduled or SDP approaches, although these do not appear to be significant for the present example. In fact, the linear PIP controller considered here has a similar implementational complexity to conventional PID-based designs, requiring only the addition of a multivariable structure and storage of additional past values. Such research demonstrates that control methods based on linearization for an operating point still have a place in the regulation of difficult nonlinear systems, especially where the extra degrees of freedom offered by the NMSS approach can be exploited to help tune the weighting terms: see reference [12] for details.

4. PROJECT PLAN REVIEW

The research largely followed the initial plan, with one major exception: the robot arm Starlifter disappeared from a trailer in 2003. Following police enquiries, the device was not recovered and eventually became the subject of an insurance claim. Research immediately switched to the excavator and vibro-lance. As planned, the EPSRC student (Matthew Stables) focused on a self-contained micro-climate test chamber project and successfully completed his thesis after 39 months, the small delay being partly attributable to the birth of his first two children. At the time of writing, he is applying for research jobs at the post-doctoral level, whilst his viva is scheduled for January 2006. Self-funded students (PhD: E. Shaban and V. Exadaktylos; MSc: S. Ako) supervised by the PI also made important contributions. The success of the planned research with Prof. Peter Young (Lancaster) and Prof. Daniel Berckmans (Leuven) is evidenced by the nine joint publications and their continued close collaboration with the PI. Finally, as described in the attached letter from Dr. A. Pike, the research with industrial partner ALSTOM was particularly important in the early stages of the project.

Note that the research has utilized a number of other nonlinear simulation examples for the development and evaluation of the methods reported above, including the IFAC93 benchmark system [8] and a macroscopic model of the M3/M27 ramp metering pilot scheme [15]. Although each practical application has specific requirements and difficulties, it is clear from these examples that NMSS / PIP control methods provide a generic approach that is able to handle a very wide range of linear and nonlinear systems.

5. RESEARCH IMPACT AND BENEFITS TO SOCIETY

The NMSS / PIP approach subsumes other modern state space and predictive control methods as constrained special cases, and so provides a very powerful and general framework for control system design. For this reason, the authors believe that the research has lead to methodology and associated software of very wide potential applicability across engineering and industry. As the present project has demonstrated, this generic framework allows for the implemention of a wide range of nonlinear techniques, of which the SDP-based approach is one of the most promising. In this regard, one advantage of SDP-PIP control, in comparison to conventional adaptive PIP control, is that the model is identified *off-line* in the former case. Therefore, the SDP approach does not require the same degree of error checking (e.g. to assess for parameter drift) as for adaptive methods. Indeed, the final SDP-PIP control algorithm is relatively straightforward to implement and, hence, attractive for industrial applications where the hardware or software may already be in place.

To the authors knowledge, the work with Bachy Soletanche Ltd represents the first fully operational use of automation for vibro-lance ground compaction, with the potential to eliminate verticality errors that had previously lead to probe repair costs of over £8000 on each occasion. One important feature designed to encourage further exploitation, is that the necessary hardware can be straightforwardly installed on (or removed from) conventional, hydraulically controlled excavators. Longer term, the robots considered in the project are likely to find application in numerous construction related activities, where they are likely to provide benefits such as reducing dependence on operator skill and a lower operator work load, both of which might be expected to contribute to more consistent improvements in quality.

On the basis of the experiments discussed above, extrapolating the reduced operating cost of the new PIP ventilation controller to the total production costs per housed animal, could yield significant savings. Other obvious applications include climate control in the human built environment, but the results potentially extend into the automotive industry and high technology areas such as the fabrication of microprocessors.

6. EXPENDITURE, DISSEMINATION AND FURTHER RESEARCH

Apart from the PhD studentship, the planned expenditure largely related to travel, primarily the partnership with Katholieke Universiteit Leuven. However, the rapid success of this part of the project allowed for some of these funds to be diverted, in part to develop a collaboration with Dr Diego Pedregal at Universidad Castilla-La Mancha (Cuidad Real). The outcome was the completion and subsequent Internet release of the Matlab© *Captain Toolbox for time series analysis and forecasting*, together with the preparation of an appropriate handbook: see reference [10] for more details. Of particular importance to the present project, the updated toolbox includes all the latest algorithms for SDP model identification and estimation. Naturally, the planned budget for Starlifter was transferred to support other activities, such as travel to Bachy Soletanche Ltd. The authors believe these have been a sensible use of funds in otherwise unforeseen circumstances.

The research has already led to 19 publications including, but not limited to [12-22]. Additional papers have been submitted in the last six months [8-10] or are in preparation. Naturally the techniques have been shared with the industrial partners. In fact, the collaboration with Bachy Soletanche Ltd was developed as a direct result of early dissemination activities and has lead to one of the most promising lines of further research. In this regard, it should be pointed out that further field tests with the vibro-lance are now required in order to more fully evaluate the robustness properties of the approach. Research also continues into more theoretical aspects of the SDP-PIP algorithm that were beyond the scope of the present project. These include proofs of controllability and stability for the conditions and model structures not covered by the results in section 2 of this report. In the latter regard, one on-going avenue of research is to utilize existing results in nonlinear control theory, such as model predictive control, within the context of non-minimal state variable feedback.

REFERENCES

1. Isidori (1995) *Nonlinear control systems*, 3rd Edition, Springer-Verlag, Berlin.
2. Leith, D.J. and Leithead, W.E. (1998) Gain-scheduled and nonlinear systems: dynamic analysis by velocity-based linearization families, *International Journal of Control*, **70**, 2, 289-317.
3. Burnham, K.J., Dunoyer, A. and Marcroft, S. (1999) Bilinear controller with PID structure, *Computing and Control Engineering Journal*, **10**, 2, 63-69.
4. Young, P.C., Behzadi, M.A., Wang, C.L. and Chotai, A. (1987) Direct digital and adaptive control by input-output, state variable feedback pole assignment, *International Journal of Control*, **46**, 1867-1881.
5. Taylor, C.J., Chotai, A. and Young P.C. (2000) State space control system design based on non-minimal state-variable feedback : Further generalisation and unification results, *Int. J. Control*, **73**, 1329-1345.
6. Young, P.C. (2000) Stochastic, dynamic modelling and signal processing, appears in *Nonlinear and nonstationary signal processing*, W.J. Fitzgerald *et al.* (Ed.), Cambridge University Press, 74-114.
7. Wang, L. and Young, P.C., (2005), Model predictive control design using non-minimum state space models, to appear in *Journal of Process Control*. See preprint – http://dx.doi.org/10.1016/j.jprocont.2005.06.016

Journal publications arising from the project, including submitted papers

8. Exadaktylos, V., Taylor, C.J., Wang, L. and Young, P.C., Model predictive control using forward path non-minimum state space models, submitted to *IEE Proceedings – Control Theory & Applications*, 30/11/05.
9. Stables, M.A. and Taylor, C.J., Nonlinear control of ventilation rate using state dependent parameter models, submitted to *Biosystems Engineering*, 30/08/2005.
10. Taylor, C.J., Pedregal, D.J., Young, P.C. and Tych, W., Environmental Time Series Analysis and Forecasting with the Captain Toolbox, submitted to *Environmental Modelling and Software*, 15/07/05, minor revisions required.
11. Taylor, C.J., Shaban, E.M. and Ako, S., Nonlinear automated verticality alignment for a vibro-lance, *in preparation*.
12. Taylor, C.J. and Shaban, E.M. (2005) Multivariable Proportional-Integral-Plus (PIP) control of the ALSTOM nonlinear gasifier simulation, to appear in *IEE Proceedings – Control Theory and Applications*.
13. Taylor, C.J. (2004) Environmental test chamber for the support of learning and teaching in intelligent control, *International Journal of Electrical Engineering Education*, **41**, 4, 375-387.
14. Taylor, C.J., Leigh, P.A., Chotai, A., Young, P.C., Vranken, E. and Berckmans, D. (2004) Cost effective combined axial fan and throttling valve control, *IEE Proceedings – Control Theory and Applications*, **151**, 5, 577-584.
15. Taylor, C.J., Mckenna, P.G., Young, P.C., Chotai, A. and Mackinnon, M. (2004) Macroscopic traffic flow modelling and ramp metering control, *Environmental Modelling and Software*, **19**, 10, 975-988.
16. Gu, J., Taylor J. and Seward, D. (2004) Proportional-Integral-Plus control of an intelligent excavator, *Journal of Computer-Aided Civil and Infrastructure Engineering*, **19**, 16-27.
17. Taylor, C.J., Leigh, P., Price, L., Young, P.C., Berckmans, D., Janssens, K., Vranken, E. and Gevers, R. (2004) Proportional-Integral-Plus (PIP) control of ventilation rate, *Control Engineering Practice*, **12**, 2, 225-233.

Selected conference publications

18. Dixon, R., Taylor, C.J. and Shaban, E.M. (2005) Comparison of classical and modern control applied to an excavator-arm, *IFAC 16th Triennial World Congress*, 4-8 July, Prague, Czech.
19. Shaban, E.M., Zied, K., Taylor, C.J. and Seward, D.W. (2005) Nonlinear control system design for construction robots, *22nd Int. Symp. on Automation and Robotics in Construction, ISARC'05*, 11-14 Sept., Ferrara, Italy.
20. Shaban, E.M. and Taylor, C.J. (2005) Proportional-Integral-Plus control of a class of nonlinear systems using exact and partial linearisaton by feedback, *Automatic Control and System Engineering*, 19-21 Dec., Cairo, Egypt.
21. Taylor, C.J., Stables, M.A. and Young, P.C. (2004) Identification of a multivariable state dependency for airflow rate in a forced ventilation test chamber, *UKACC Control 2004*, Paper-60, 6-9 Sept., Bath, UK.
22. Gu, J., Taylor, J. and Seward, D. (2004) Proportional-Integral-Plus (PIP) Gain scheduling control of an intelligent excavator, *21st Int. Symp. on Automation and Robotics in Construction, ISARC'04*, 21-25 Sept., Jeju, Korea.