Keynote 2

An overview of ACTLab research at the University of Bristol - and our links with Japan -

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Abstract
This paper summarises the content of the associated keynote presentation, one objective of which is to outline the development of the Advanced Control and Test Laboratory (ACTLab) at the University of Bristol, since its original inception in 1999, together with an appraisal of the research that is conducted in the laboratory. Hence, aspects of our work on adaptive control, dynamically substructured systems, data fusion and associated experimentation will be included in the talk.

The other objective of the presentation is to place due emphasis on ACTLab links with Japanese researchers, since they have had (and continue to have) a very significant impact on the laboratory – both in terms of fundamental concepts and the associated application and implementation of the ideas.

Keywords: Bristol Laboratories for Advanced Dynamic Engineering (BLADE), Advanced Control and Test Laboratory (ACTLab), MCS Adaptive Control, Dynamic Substructuring Control, Composite Filtering, Servohydraulic System Control, Shaking Table Control

1. Introduction

Since its origins in the first few years of the 20th century, the Faculty of Engineering at the University of Bristol has maintained its position as one of the most successful research institutions in the UK. Throughout these years, collaboration between researchers in the traditional departments of mechanical, civil and aerospace engineering continued apace at a consistently high level, despite the fact that the associated laboratories were solidly based within their respective departments. However, by the end of the 1990s, it was recognised that a more unified and less compartmentalised approach was necessary in order to progress our research still further. Thus, the construction and development of a new facility – subsequently to be known as the Bristol Laboratories for Advanced Dynamics Engineering (BLADE) - became a priority. The BLADE initiative was proposed and led by a small team consisting of David Stoten (Mechanical Engineering), Colin Taylor (Civil Engineering) and Nick Lieven (Aerospace Engineering).

As implied by its name, the unifying theme behind BLADE was a focus on dynamics – and nonlinear dynamics in particular – a theme that was to encompass the fields of control engineering, nonlinear dynamics, structural dynamics, dynamic substructuring, materials engineering, earthquake engineering and geotechnical engineering. Central to BLADE was the concept of advanced dynamic testing, which would make use of the latest developments in automatic control and dynamic substructuring methods. Correspondingly, at the geographic and philosophical centre of BLADE, a new Advanced Control and Test Laboratory (ACTLab) was to be established.

By 1999 the proposal for BLADE was finalised and submitted to the UK government's Joint Infrastructure Fund committee for assessment. Against very strong competition from around the UK, the BLADE project was approved for funding. We received an amount of £15m, which at that time was the largest award ever to be made to the UK academic engineering community. This figure was complemented by a further amount from the university, making a total figure of £20m (about 50 billion in the exchange rate of the time). After a period of intense planning, BLADE construction started in 2001 and was completed on time and on budget (Fig.1), the laboratories becoming fully operational in 2004 (Fig. 3). On 25th February 2005, BLADE was officially opened by HM Queen Elizabeth II; see Fig. 2.
As shown in Fig. 3, one of the principal facilities in the ACTLab is a modular servohydraulic test system, consisting of a reconfigurable bed-plate/frame system supporting 8×30kN actuators with hydrostatic bearings, 2×4-channel inner-loop controllers for the actuators and a set of outer-loop dSPACE digital control systems. The inner-loop hardware provides essential safety interlocks, signal conditioning and servohydraulic drives, together with a nominal fixed gain (typically proportional) control $u$, determined from the test rig output $y$. Thus, in Fig. 4, the system to be controlled (the plant) is the combination of the inner-loop controller, actuator(s) and test rig. The outer-loop dSPACE system then provides a higher level control signal $u$ (adaptive, robust, multivariable, etc.), so that the measured plant output $y = y_i$ closely tracks the reference signal $r$. 
Current research interests in the ACTLab include the following topics:

- General control analysis and synthesis of robust multivariable systems.
- Adaptive control with a focus on the minimal control synthesis (MCS) algorithm.
- Dynamically substructured systems (DSS) and their control.
- Control of nonlinear systems, including chaotic systems.
- The concept of the inerter and synthesis of minimal passive dynamic systems.
- Data fusion via composite filtering methods.
- Servohydraulic system control.
- Electrical drive control.
- Control of robotic devices (in conjunction with the Bristol Robotics Laboratory).

This presentation will briefly outline just some of the achievements of ACTLab, paying particular attention to our research in the following three areas that have been influenced by our longstanding relationships with colleagues from Japan:

(i) The adaptive MCS algorithm for control of shaking tables, demand generation, electrical drives and geotechnical systems, (§2).
(ii) Analysis and synthesis of controllers for DSS, including base isolation system testing and active suspension design, (§3).
(iii) Composite filtering for demand generation and acceleration control of shaking tables, (§3).

2. The adaptive minimal control synthesis (MCS) algorithm

The adaptive minimal control synthesis (MCS) algorithm was conceived by Stoten (1989) and Stoten and Benchoubane (1990b), in order to overcome the principal problems associated with controlling robotic devices. The basic closed-loop configuration of MCS is shown in Fig. 6, which is often implemented as an outer-loop configuration around an existing (fixed-gain) controller/plant combination.
The MCS gains \( \{K_r(t), K_x(t)\} \), shown in continuous time format in Eq. (1), are computed from signals around the loop: the reference signal \( r \), the plant state response \( x \) and the state error \( x_e = x_m - x \), where \( x_m \) is the ideal response generated by a user-defined reference model.

\[
\begin{align*}
\text{Forward gain:} & \quad K_r(t) = \alpha \int_0^t y_r(\tau)x^T(\tau)d\tau + \beta y_r(t)x^T(t) \\
\text{Feedback gain:} & \quad K_x(t) = \alpha \int_0^t y_x(\tau)r^T(\tau)d\tau + \beta y_x(t)r^T(t)
\end{align*}
\]

In Eq.(1) \( \alpha, \beta > 0 \) are scalar adaptive weights (selected empirically), \( y_r = C_r x_r \) is the output error and \( C_x \) is a design parameter that ensures strict positive realness within the closed-loop error dynamics; Stoten and Benchoubane (1990). The corresponding adaptive control signal \( u \) is then generated according to Eq.(2) so that \( x_e \rightarrow 0 \), despite the presence of the external disturbance \( d \) and unknown internal parameter variations within the plant dynamics:

\[
u(t) = K_r(t)r(t) + K_x(t)x(t)
\]

Since the first publications on the subject, MCS has been developed into a family of adaptive controllers that are applicable to systems with multivariable and nonlinear dynamics, e.g. Stoten and Hodgson (1991); Hodgson and Stoten (1999). In terms of implementation of the algorithm, particular attention has been paid to the effects of noise and high-order dynamic effects that would otherwise induce adaptive parameter (gain) drift. Applications of MCS that directly resulted from ACTLab-based research have been reported in a wide range of areas, for example:

(a) In the field of servohydraulically actuated (test) systems:
- Servohydraulic actuator control; Stoten (1992)
- Materials testing machine control; Stoten and Smith (1993)
- Shaking table and reaction wall control; Stoten and Gomez (2001)
- Dynamic substructuring control; Stoten et al. (2009)
- Magneto-rheological damper test and control; Tu et al. (2010)

(b) In the field of the electrical (drive) and electronic systems:
- DC servomotor and linear drive system control; Stoten and Benchoubane (1990a), Shimono et al. (2010)
- AC induction motor control; Bowes et al. (1996)
- Robotic manipulator trajectory and force (hybrid) control; Stoten and Hodgson (1992)
- Web tension and transport control; Stoten et al. (1994)
- Adaptive linearization of communications amplifiers; Xiao et al. (2008)

(c) In a more general field of control applications:
- Feedforward control; Stoten and Shimizu (2007)
- Chaotic system control; Stoten and Di Bernardo (1996)
- Environmental systems; Stoten (1989)
- Fluidized-bed control; Harrison et al (2006)
- Automotive engine mount and vibration isolation; Hillis et al. (2005)
- Nonlinear high-α aircraft flight control; Wang, et al. (2003)
Successful applications of MCS have also been extensively reported by authors who are independent of ACTLab and its personnel. Examples include work on the control of nonlinear systems (Di Bernardo et al. (2010)), vehicle dynamics (Catino et al. (2003)), shaking tables (Shen et al. (2011)), servohydraulic systems (Gizatullin and Edge (2007)), electrical drives (Naceri and Abida (2003); Kwon et al. (2001)), structural and vibration systems (Ma et al. (2011); Tu et al. (2014)); aerospace systems (Arif (2008)) and pneumatic systems (Ito et al. (2008)).

A summary of research on the MCS algorithm, with specific links to Japanese teams, now follows.

A joint team from Iwaki Meisei University and the National Research Institute for Earth Sciences and Disaster Prevention (NIED) have reported the results of applying MCS to the problem of horizontal acceleration control of a multi-axis shaking-table; e.g. Shimohara et al., (2006). The adaptive algorithm was applied in tandem with conventional fixed-gain three-variable control (TVC) policy. When compared with the use of TVC alone, the addition of MCS resulted in marked improvements in tracking response, especially when a non-linear structure was attached to the table. In addition, the influence of specimen resonance on the table motion was effectively cancelled by the MCS algorithm, as was the potential for coupled pitching motion induced by specimen inertia.

The collaborative link with Professor Shimizu at Iwaki Meisei University also led to the formulation of an MCS-based adaptive feedforward control, Stoten and Shimizu (2007), and again this was applied to the problem of multi-axis shaking-table control as an additional loop to TVC. The motivation for feedforward-only adaptive control was based on operator restrictions to the feedback loops for shaking-tables; specifically, alteration of feedback loops away from the standard TVC configuration was often explicitly forbidden. The authors showed that, subject to preservation of global stability by the TVC feedback loops, feedforward MCS would consistently generate ∼20% performance improvements over a well-tuned TVC scheme, based upon an integral-square-error performance criterion.

Another form of feedforward control was developed in conjunction with Professor Tagawa at Tokyo University of Agriculture and Technology (TUAT), called the method of inverse dynamics compensation via simulation of feedback control systems (IDCS); Tagawa et al. (2011). This novel technique essentially consists of a real-time simulation of the closed-loop plant to generate an idealised control signal, which is then used as a feedforward component of the actual control signal to the real plant. The method relies on an accurate plant model being available, which can be discontinuous and nonlinear, obviating the need for alternative, more complex, techniques such as explicit model inversion. Moreover, the simulation will often contain noise free signals, so that high gain controllers can be used to provide high precision in the generation of the feedforward control signal. Often, IDCS is also used in conjunction with a more softly tuned feedback loop, in order to provide robustness against parameter unknowns. In Tagawa et al. (2011) a version of MCS was used within the IDCS loop to control a kinematically nonlinear servohydraulic system, yielding excellent tracking performance, even in a feedforward-only configuration.

In a similar vein, Dr Kajiwara (Director of NIED's E-Defense shaking-table facility at Miki-shi), Dr Enokida (Kyoto University) and Professor Nakashima (Kyoto University) have developed a method of demand (i.e. reference signal) generation that uses MCS in an off-line or on-line manner; Kajiwara et al. (2012). The problem is to determine the appropriate reference signal to a shaking table controller, so that the response of a (nonlinear) specimen at a specific location is close to a given reference signal. A combined model of the table system and specimen is used within a closed-loop MCS simulation to determine an ideal control signal from the reference and corresponding response signals. This ideal control signal is then used as the actual reference signal to the (TVC) controller on the physical shaking-table. Experiments conducted on the shaking table at Kyoto University confirmed the efficacy of this MCS-based approach, which outperformed an $H_{\infty}$ based comparator by a significant degree.

Research with Professor Koganezawa, Tokai University, Hiratsuka, Kanagawa, focussed on the use of MCS for the control of hyper-redundant manipulators with serial links; Koganezawa and Stoten (2008). Due to the large number of degrees of freedom in such devices, the associated dynamics are relatively complicated, non-linear, and subject to a high level of parameter uncertainty. This makes the control problem particularly difficult to solve and therefore a development of MCS, which also took account of link constraints and introduced anti-windup protection into the algorithm, was used in this application. In Koganezawa and Stoten (2008), a simulation of a 4-link manipulator resulted in close reference tracking, even though the controller gain matrices (with 64 gain entries in total) had zero initial conditions.

Professor Maeda's group in the Department of Civil Engineering, Nagoya Institute of Technology, makes extensive
use of the discrete element method (DEM) to simulate macro-scale geotechnical phenomena such as rock fall and dam bursting. DEM dynamics are highly nonlinear, so that traditional controllers (such as PID) have been used in order to stabilise the simulation integration routines. However, it has been found that the controller gains are difficult to tune and once the simulation parameters have changed (this can happen during the simulation itself), a new set of gains have to be determined. Therefore MCS was a natural candidate for solving this problem and, in this on-going research, the algorithm has provided consistent and stable simulation responses in a number of pilot studies.

Design and experimentation by Professor Tagawa and Dr Shimono at TUAT, on the application of a new version of the algorithm (called reference-state MCS; Hatano (2013)) to a linear electrical drive system, showed that excellent tracking control is achieved over an extended test period, without any signs of gain wind-up or drift. The reference-state MCS algorithm uses only reference model state information for direct feedback, but it does use plant state information for gain generation. In this way, gain wind-up due to noise, unmodelled higher order dynamics and nonlinearity is largely obviated, with gains achieving quasi-static values after an initial transient phase.

Finally, a collaborative project with Toshiba Telecommunications Research Laboratories, Bristol, into the linearization of mobile communication device radio frequency amplifiers is described in Xiao et al. (2008). The problem was centred on achieving a virtually distortion free amplifier characteristic, even though the original amplifier was highly nonlinear and subject to parameter variations. The nonlinear characteristics of the amplifier were effectively devoid of dynamic content, consisting of a static, nonlinear input-output relationship. To take account of this, a modified version of the feedforward MCS algorithm was utilised, having the function of an adaptive pre-distortion filter, so that energy efficiency was preserved due to the absence of any direct feedback loops. Xiao et al. (2008) report the high level of linearization achieved across the amplifier operating range.

3. Dynamically substructured systems (DSS)

In recent years, there has been significant interest in using the principle of dynamically substructured systems (DSS) as a framework for the testing of critical engineering components and systems. The advantage of the method is that it offers the opportunity to test full size nonlinear components within a laboratory environment. Such a test would be run in parallel with a real-time numerical simulation of the remaining part of the overall system to be emulated. Potentially, a disadvantage of the method is the very high fidelity of control that is required, in order to achieve near perfect synchronization of the test rig and the numerical model. This problem is further exacerbated by the presence of unknown and changing dynamic parameters, disturbances, discrete computation delays and nonlinearity in the test rig.

Hence, ACTLab research has been addressing such problems, with control solutions presented in both the linear and nonlinear (adaptive) domains; e.g. Stoten and Hyde (2006); Stoten et al. (2009).

A schematic representation of the original formulation for DSS is shown in the left-hand diagram of Fig. 7, where an emulated system (\( \Sigma_x \)) is decomposed into a numerical (\( \Sigma_y \)) and a physical substructure (\( \Sigma_p \)). Also shown is the interaction constraint \( f_i \) (typically a force), between the substructures, the system excitation \( d \), the substructure outputs \( \{y_{n1}, y_{n2}\} \), (typically displacements) and the DSS control signal \( u \), which has the prime purpose of ensuring \( y_{n1} \rightarrow y_{n2} \) in a stable and robust manner. Also evident in the diagram is the ancillary hardware associated with \( \Sigma_p \) and collectively known as the transfer system, i.e. actuator(s), test frame structure/mechanism, inner-loop controller and sensor(s).

Ideally, the effect of \( u \) should also be to cancel dynamical effects, i.e. gain and phase modulation, introduced by the transfer system. In terms of a general, linear representation of the DSS, Stoten and Hyde (2006) formulated the equivalent transfer function (matrix) block diagram shown on the right of Fig. 7, consisting of the triple \( \{G_0, G_1, G_2\} \) together with the synchronisation error \( e = y_{n2} - y_{n1} \).

Assigning \( G_d = G_1 \) and \( G_u = G_0 + G_2 \), the DSS is recognised as the parallel model-following structure shown in Fig. 8 and, although having transformed outputs \( \{z_1, z_2\} \), this formulation retains the original synchronisation error, \( e \), in explicit form. In brief, we define a linear substructuring controller (LSC) as:

\[
u(s) = K_y(s)d(s) + K_x(s)e(s)\tag{3}\]

so that the closed-loop error dynamics are governed by:

\[
e(s) = [I + G_u(s)K_y(s)]^{-1}[G_y(s) - G_x(s)K_x(s)]d(s)\tag{4}\]
Hence, a solution to this two degree-of-freedom (DOF) control problem is to assign the forward loop gain as:

\[ K_d(s) = G^{-1}_u(s)G_d(s) \]  

(5)

and \( K_d \) in the closed-loop characteristic equation, \([I + G_cK_d] = 0\), can be designed to ensure stability and robustness via any of the well-known techniques (e.g. the classic roots' loci method).

**Fig. 7** Dynamically substructured system (DSS). *left*: conceptual diagram; *right*: equivalent block representation

**Fig. 8** Linear substructuring controller (LSC) and the equivalent model-following DSS structure

Until comparatively recently, implementations of the DSS testing method has been confined to internal ACTLab research projects and associated test rigs, such as the quasi-motorcycle rig shown in Fig. 5 and multivariable m-k-c hydraulically actuated systems, representing multi-stage shaking-tables; Hatano (2013). However, since 2012 there has been a shift to DSS research involving outside institutions, some of them from Japan.

For example, work with Messrs Watanabe and Yamaguchi from the Railway Technical Research Institute (RTRI), Kokubunji, Tokyo, is focusing on the use of DSS synthesis procedures for the design of an active controller for a rapid prototyping bogie (RPB), used to test suspension designs for shinkansen carriages; see Fig. 9 *(top)*. Thus far, synthesis of DSS within a state-space framework has generated significantly improved results compared with previously used classical tuning methods, especially with respect to sensor noise suppression and dynamic decoupling between the 18 DOF of the system. For example, at a certain critical speed, limit cycle behaviour is known to be present in a conventional bogie system. Fig. 9 *(bottom)* shows the corresponding response of the conventional bogie, together with that of the RPB; clearly there is a very close correspondence between them. The ensuing RTRI test programme for these concepts is scheduled to be completed at Kokubunji during the period 2015-16.
Research with Professor Nakashima, Professor Takewaki and Dr Enokida from Kyoto University, on the application of DSS to the test of seismic mitigation devices for buildings, is also generating very promising results, Enokida and Stoten (2014). Implementation of the concept on a pilot study DSS base isolation system within the ACTLab, which consists of a rubber bearing and two servohydraulic actuators representing ground excitation and structural interaction, has shown that the DSS technique is significantly more robust to computational pure delay than an equivalent hybrid test scheme; see Fig 10. Moreover, a direct spin-off from this research has been the development of new methods for single-input, multi-output input identification for shaking table tests (Enokida et al. (2014)) and, separately, a novel form of nonlinear substructuring control (NSC) for DSS; see Fig. 11.

Fig. 9  top: rapid prototyping bogie (actuators shown in red);  
bottom: response of the actual bogie system ('Reference') and the DSS-designed RPB ('Rapid'), showing limit cycles

Fig. 10  top: Base isolation test rig;  
bottom: comparative hybrid and DSS tests when the pure delay in the discrete-time loops is $\tau = 6\text{ms}$. 

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4. Composite filtering

The concept of composite filtering, a form of data fusion, was presented in Stoten (2001) and was initially motivated by problems in controlling shaking-tables across a relatively wide frequency band. In this context, the principle problem associated with displacement control (for example) is that at the table motion is vanishingly small at high frequencies, so that quantisation errors in measurements, sensor noise and mechanism backlash can cause a lack of tracking fidelity, especially when viewed as a power spectrum density curve of the corresponding acceleration. On the other hand, the problem of acceleration control is that accelerometer performance at low frequencies is poor and also acceleration control per se will often lead to unwanted drift in the table displacement, ultimately resulting in an encounter with end-limits.

Composite filtering was devised to overcome such problems, whether displacement, velocity or acceleration control was the main mode of operation of the table, so that enhanced control (without drift) could be obtained over a wide frequency band. Fig. 12 shows a typical composite Butterworth filter structure, in this case for obtaining a wide-band signal for displacement from the raw acceleration and displacement data. The only parameter required in the synthesis of the filter is the break frequency, $a$, the 'dividing line' between displacement data and acceleration data integrity.

Fig. 12  left: composite Butterworth filter (called ad2d in this case) for wide-band synthesis of displacement.
right: corresponding Bode plots for the ad2d filter when $a = 20$rad/s
Thus, in Stoten (2001), a set of 10 composite filters was devised, each satisfying the following criteria:

(i) Measured signals can have non-zero means and measured derivatives can exhibit drift.
(ii) Measured acceleration (velocity) signals can be integrated twice (once), but the effects of the bias and drift must be removed after a suitably short transient period.
(iii) The signal from (ii) is filtered by the high-pass component of a complementary filter.
(iv) Measured displacement signals are filtered by the low-pass component of the complementary filter.
(v) Filter components must be proper and of minimal order.
(vi) The gain and phase of the resulting composite filter are unity and zero, respectively.

Composite filters can be used in data processing, demand generation (e.g. determining displacement demand from a pre-recorded acceleration signal) and in real-time control loops. An example of the latter, the indirect acceleration control with composite filter (IACC) method is shown in Fig. 13. Here, only the high pass component filter (acceleration to displacement) is used to generate a displacement demand signal, off-line or on-line, whilst both components are used on-line in the feedback loop to generate a wide-band displacement response. Note that the controller and composite filter designs are independent of one another. Hatano (2013) has shown in experiments that this arrangement does indeed yield high fidelity responses across a wide frequency band and that it significantly outperforms a more direct acceleration control scheme.

![IACC method for acceleration control](image)

Fig. 13 IACC method for acceleration control

More recent research has shown that the controller fusion method of Professor Tagawa can have similar characteristics to those of the composite filtering method. For this reason Shimono et. al (2014) have formulated a unified description of the two methods, testing this new concept on the displacement control of a servohydraulic actuator in the ACTLab, using both displacement and acceleration feedback. Experiments show that the unified synthesis method, whether via the controller fusion or the composite filter approach, yields remarkably similar results, thus supporting the validity of the method.

5. The future

To conclude this presentation, the following plans for the future are summarised below; their scope will be for the short-medium term and they constitute the next stage of ACTLab-Japan research:

- Further development of the MCS algorithm with Dr Kajiwara (NIED) and Dr Enokida (Kyoto University) on the basic motion control of shaking-tables, together with the control of shaking-tables for DSS experimentation on base isolation systems, tuned mass/active mass dampers, soil-structure interactions and liquefaction problems; on-line identification of physical substructures for enhanced DSS accuracy; the use of composite filtering techniques for shaking-table control and demand generation.
- Development of the NSC-DSS and the underlying nonlinear signal based control methodologies with Dr Enokida and colleagues from the University of Kyoto.
- Model reduction methods for numerical substructures in DSS schemes, with Professor Fujimoto, Department
of Aeronautics and Astronautics, Kyoto University.

- Design of controllers for active suspension systems with Mr Yamaguchi (RTRI); unification of model reference control and DSS methodologies.
- Use of composite filtering within RTRI systems; development of a major UK-Japan research programme for virtual roller test systems using DSS methodologies.

Acknowledgements

I would like to thank the following Japanese colleagues for their continuous support, encouragement and insights into the dynamics and control of general systems and also into the dynamics of civil engineering systems: Professors Nobuyuki Shimizu (Iwaki Meisei University), Yasutaka Tagawa (Tokyo University of Agriculture and Technology), Koichi Koganezawa (Tokai University, Kanagawa), Kenichi Maeda (Nagoya Institute of Technology), Masayoshi Nakashima (Kyoto University), Izuru Takewaki (Kyoto University), Masayuki Hyodo, (Yamaguchi University) and Kenji Fujimoto (Kyoto University); Drs Kenichi Kajiwara (E-Defense, National Research Institute for Earth Sciences and Disaster Prevention), Kimiaki Sasaki (Railway Technical Research Institute), Toshiaki Hatano (University of Bristol), Ryuuta Enokida (Kyoto University/University of Bristol) and Keisuke Shimono (Tokyo University); Messrs. Nobuyuki Watanabe (Railway Technical Research Institute), Teruya Yamaguchi ((Railway Technical Research Institute), Ryuichi Hatano (University of Bristol) and Akihiko Kondo (Nagoya Institute of Technology). Not least, I wish to thank them for their unstinting friendliness and warm welcome whenever I visit Japan.

Some names have probably been overlooked in the compilation of this list and I apologise for such omissions.

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