Intermittent Control Publications of Peter Gawthrop

[1] E. Ronco, T. Arsan, and P. J. Gawthrop. Open-loop intermittent feedback control: Practical continuous-time GPC. *IEE Proceedings Part D: Control Theory and Applications*, 146(5):426--434, September 1999. [bib | DOI]

A conceptual, and practical difficulty with the continuous-time generalised predictive controller is solved by replacing the continuously moving horizon by an intermittently moving horizon. This allows slow optimisation to occur concurrently with a fast control action. Some nonlinear simulations illustrate the potential of this approach.

[2] Peter J. Gawthrop and Liuping Wang. Intermittent predictive control of an inverted pendulum. *Control Engineering Practice*, 14(11):1347--1356, November 2006. [bib | DOI]

Intermittent predictive pole-placement control is successfully applied to the constrained-state control of a prestabilised experimental inverted pendulum.

[3] Peter J Gawthrop and Liuping Wang. Intermittent model predictive control. *Proceedings of the Institution of Mechanical Engineers Pt. I: Journal of Systems and Control Engineering*, 221(7):1007--1018, 2007. [bib | DOI]

Intermittent control, where a sequence of open-loop trajectories are punctuated by intermittent feedback, is described and a number of design methods presented. A generalised hold representation is derived and shown to be useful for both implementation and analysis. The relationship between predictive control of a time delay system and intermittent control is examined and it is shown that a simplified predictor can be used in the latter case.

The applicability of intermittent control to the implementation of MPC is discussed and illustrated by the control of a difficult mechanical system -- a self-balancing seesaw.

[4] Peter J. Gawthrop and Liuping Wang. Constrained intermittent model predictive control. *International Journal of Control*, 82:1138--1147, 2009. Published online 27 January 2009. [bib | DOI]

The generalised hold formulation of intermittent control is re-examined and shown to have some useful theoretical and practical properties. It is shown that this provides a foundation for constrained model predictive control in an intermittent context. The method is illustrated using an example and verified with experimental results.

[5] Peter J Gawthrop. Frequency domain analysis of intermittent control. *Proceedings of the Institution of Mechanical Engineers Pt. I: Journal of Systems and Control Engineering*, 223(5):591--603, 2009. [bib | DOI]

Intermittent control is a feedback control design method that combines both continuous-time and discrete-time domains; a recent result shows that this form of intermittent control can be rewritten as a sampled-data feedback system with a particular vector generalised hold. This paper builds on this result to give, for the first time, a frequency domain analysis of the closed-loop system containing an intermittent controller.

This analysis is illustrated using two examples. The first example is related to the human balance control system and us thus physiologically relevant. The second example gives a theoretical explanation of the phenomenon of self-induced oscillations in intermittent control systems.

[6] P.J. Gawthrop. Act-and-wait and intermittent control: Some comments. *IEEE Transactions on Control Systems Technology*, 2009. Published on-line: 10/11/2009. [bib | DOI]

The act-and-wait control introduced by Insperger is shown to be related to a form of intermittent control. Theoretical and practical similarities and differences between the two methods are explored.

[7] Peter J Gawthrop and Liuping Wang. Event-driven intermittent control. *International Journal of Control*, 82(12):2235 -- 2248, December 2009. Published online 09 July 2009. [bib | DOI]

An intermittent controller with fixed sampling interval is recast as an event-driven controller. The key aspect of intermittent control that makes this possible is the use of basis functions, or, equivalently, a generalised hold, to generate the intersample open-loop control signal. The controller incorporates both feedforward events in response to known signals and feedback events in response to detected disturbances. The latter feature makes use of an extended basis-function generator to generate open-loop predictions of states to be compared with measured or observed states. Intermittent control is based on an underlying continuous-time controller; it is emphasised that the design of this continuous-time controller is important, particularly in the presence of input disturbances. Illustrative simulation examples are given.

[8] Peter J. Gawthrop and Liuping Wang. Intermittent redesign of continuous controllers. *International Journal of Control*, 83:1581--1594, 2010. [bib | DOI]

The reverse-engineering idea developed by Maciejowski in the context of model-based predictive control is applied to the redesign of continuous-time compensators as intermittent controllers. Not only does this give a way of designing constrained input and state versions of continuous-time compensators but also provides a method for turning continuous-time compensators into event-driven versions. The procedure is illustrated by three examples: an event-driven PID controller relevant to the human balance control problem, a constrained version of the classical mechanical vibration absorber of den Hartog and an event driven and constrained vibration absorber.

[9] Ian David Loram, Henrik Gollee, Martin Lakie, and Peter Gawthrop. Human control of an inverted pendulum: Is continuous control necessary? Is intermittent control effective? Is intermittent control physiological? *The Journal of Physiology*, 589:307--324, 2011. Published online November 22, 2010. [bib | DOI]

Human motor control is often explained in terms of engineering â³servoâ³ theory. Recently, continuous, optimal control using internal models has emerged as a leading paradigm for voluntary movement. However, these engineering paradigms are designed for high bandwidth, inflexible, consistent systems whereas human control is low bandwidth and flexible using noisy sensors and actuators. By contrast, engineering intermittent control was designed for bandwidth-limited applications. Our general interest is whether intermittent rather than continuous control is generic to human motor control. Currently, it would be assumed that continuous control is the superior and physiologically natural choice for controlling unstable loads, for example as required for maintaining human balance. Using visual manual tracking of an unstable load, we show that control using gentle, intermittent taps is entirely natural and effective. The gentle tapping method resulted in slightly superior position control and velocity minimisation, a reduced feedback time delay, greater robustness to changing actuator gain and equal or greater linearity with respect to the external disturbance. Control was possible with a median contact rate of 0.8Â±0.3 s-1. However, when optimising position or velocity regulation, a modal contact rate of 2s-1 was observed. This modal rate was consistent with insignificant disturbance-joystick coherence beyond 1-2 Hz in both tapping and continuous contact methods. For this load, these results demonstrate a motor control process of serial ballistic trajectories limited to an optimum rate of 2 s-1. Consistent with theoretical reasoning, our results suggest that intermittent open loop action is a natural consequence of human physiology.

[10] Peter Gawthrop, Ian Loram, Martin Lakie, and Henrik Gollee. Intermittent control: A computational theory of human control. *Biological Cybernetics*, 104(1-2):31--51, 2011. Published online: 17th February 2011. [bib | DOI]

Human motor control is often explained in terms of engineering â³servoâ³ theory. Recently, continuous, optimal control using internal models has emerged as a leading paradigm for voluntary movement. However, these engineering paradigms are designed for high bandwidth, inflexible, consistent systems whereas human control is low bandwidth and flexible using noisy sensors and actuators. By contrast, engineering intermittent control was designed for bandwidth-limited applications. Our general interest is whether intermittent rather than continuous control is generic to human motor control. Currently, it would be assumed that continuous control is the superior and physiologically natural choice for controlling unstable loads, for example as required for maintaining human balance. Using visual manual tracking of an unstable load, we show that control using gentle, intermittent taps is entirely natural and effective. The gentle tapping method resulted in slightly superior position control and velocity minimisation, a reduced feedback time delay, greater robustness to changing actuator gain and equal or greater linearity with respect to the external disturbance. Control was possible with a median contact rate of 0.8Â±0.3 s-1. However, when optimising position or velocity regulation, a modal contact rate of 2s-1 was observed. This modal rate was consistent with insignificant disturbance-joystick coherence beyond 1-2 Hz in both tapping and continuous contact methods. For this load, these results demonstrate a motor control process of serial ballistic trajectories limited to an optimum rate of 2 s-1. Consistent with theoretical reasoning, our results suggest that intermittent open loop action is a natural consequence of human physiology.

[11] Peter Gawthrop and Liuping Wang. The system-matched hold and the intermittent control separation principle. *International Journal of Control*, 84(12):1965--1974, 2011. [bib | DOI]

An intermittent controller is a form of hybrid controller which adds a generalised sample and hold mechanism to an underlying continuous-time feedback control system. The sampling may be non-uniform or event driven. One particular form of the hold, termed the system-matched hold (SMH) mimics the behaviour of the closed-loop feedback control signal during the intermittent intervals. It is shown in this article that this choice of hold leads to an intermittent separation principle. In particular, this simple analytical result ensures that when using the SMH, the separation properties of the underlying state-estimate feedback control system carry over to the intermittent control system. This separation principle for the SMH has the important consequence that, unlike the zero-order hold case, the stability of the closed-loop system in the fixed sampling case is not dependent on sample interval. It is therefore suggested that the SMH should replace the conventional zero-order hold in circumstances where the sample interval is unknown, time-varying or determined by events.

[12] Peter J. Gawthrop, Simon A. Neild, and David J. Wagg. Semi-active damping using a hybrid control approach. *Journal of Intelligent Material Systems and Structures*, 2012. Published online February 21, 2012. [bib | DOI]

In this article, a hybrid control framework is used to design semi-active controllers for vibration reduction. It is shown that the semi-active skyhook damper, typically used for vibration reduction, can be recast in the framework of an event-driven intermittent controller. By doing this, we can then exploit the well-developed techniques associated with hybrid control theory to design the semi-active control system. Illustrative simulation examples are based on a 2 degree-of-freedom system, often used to model the dynamics of a quarter car body model. The simulation results demonstrate how hybrid control design techniques can improve the overall performance of the semi-active control system.

[13] Ian D. Loram, Cornelis van de Kamp, Henrik Gollee, and Peter J. Gawthrop. Identification of intermittent control in man and machine. *Journal of The Royal Society Interface*, 9(74):2070--2084, 2012. Published on-line April 4, 2012. [bib | DOI]

Regulation by negative feedback is fundamental to engineering and biological processes. Biological regulation is usually explained using continuous feedback models from both classical and modern control theory. An alternative control paradigm, intermittent control, has also been suggested as a model for biological control systems, particularly those involving the central nervous system. However, at present, there is no identification method explicitly formulated to distinguish intermittent from continuous control; here, we present such a method. The identification experiment uses a special paired-step set-point sequence. The corresponding data analysis use a conventional ARMA model to relate a theoretically derived equivalent set-point to control signal; the novelty lies in sequentially and iteratively adjusting the timing of the steps of this equivalent set-point to optimize the linear time-invariant fit. The method was verified using realistic simulation data and was found to robustly distinguish not only between continuous and intermittent control but also between event-driven intermittent and clock-driven intermittent control. When applied to human pursuit tracking, event-driven intermittent control was identified, with an intermittent interval of 260â310 ms (n = 6, p < 0.05). This new identification method is applicable for machine and biological applications.

[14] Peter J Gawthrop and Henrik Gollee. Intermittent tapping control. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 226(9):1262--1273, 2012. Published online on July 26, 2012. [bib | DOI]

Control using a sequence of âtapsâ, in contrast to the usual smooth control, is shown to fit within the established intermittent control framework. In particular, a specially designed generalised hold gives rise to tapping behaviour optimised according to the underlying linear-quadratic design. Both fixed-interval and event-driven tapping are included in this approach and some basic stability analysis is given. Illustrative examples are presented and the advantages of tapping in the context of electromechanical servo systems with friction are explored using a laboratory experiment.

[15] H. Gollee, A. Mamma, I. D. Loram, and P. J. Gawthrop. Frequency-domain identification of the human controller. *Biological Cybernetics*, 106:359--372, 2012. Published online: 14 July 2012. [bib | DOI]

System identification techniques applied to experimental human-in-the-loop data provide an objective test of three alternative controlâtheoretical models of the human control system: non-predictive control, predictive control, and intermittent predictive control. A two-stage approach to the identification of a single-input single-output control system is used: first, the closed-loop frequency response is derived using the periodic property of the experimental data, followed by the fitting of a parametric model. While this approach is well-established for non-predictive and predictive control, it is here used for the first time with intermittent predictive control. This technique is applied to data from experiments with human volunteers who use one of two control strategies, focusing either on position or on velocity, to manually control a virtual, unstable load which requires sustained feedback to maintain position or low velocity. The results show firstly that the non-predictive controller does not fit the data as well as the other two models, and secondly that the predictive and intermittent predictive controllers provide equally good models which cannot be distinguished using this approach. Importantly, the second observation implies that sustained visual manual control is compatible with intermittent control, and that previous results suggesting a continuous control model for the human control system do not rule out intermittent control as an alternative hypothesis. Thirdly, the parameters identified reflect the control strategy adopted by the human controller.

[16] Peter Gawthrop, David Wagg, Simon Neild, and Liuping Wang. Power-constrained intermittent control. *International Journal of Control*, 86(3):396--409, 2013. Published online 30 Oct 2012. [bib | DOI]

In this article, input power, as opposed to the usual input amplitude, constraints are introduced in the context of intermittent control. They are shown to result in a combination of quadratic optimisation and quadratic constraints. The main motivation for considering input power constraints is its similarity with semi-active control. Such methods are commonly used to provide damping in mechanical systems and structures. It is shown that semi-active control can be re-expressed and generalised as control with power constraints and can thus be implemented as power-constrained intermittent control. The method is illustrated using simulations of resonant mechanical systems and the constrained nature of the power flow is represented using power-phase-plane plots. We believe the approach we present will be useful for the control design of both semi-active and low-power vibration suppression systems.

[17] Cornelis van de Kamp, Peter J. Gawthrop, Henrik Gollee, and Ian D. Loram. Refractoriness in sustained visuo-manual control: Is the refractory duration intrinsic or does it depend on external system properties? *PLoS Comput Biol*, 9(1):e1002843, 01 2013. [bib | DOI]

In biology, the control of physiological variables such as body position, blood pressure and body temperature is founded on negative feedback mechanisms governing homeostasic input-output relations. The conceptual models capturing the underlying control principles are often drawn from engineering control theory. The visuo-manual control of external systems (like balancing a stick on the palm of one's hand) has traditionally been interpreted using continuous paradigms such as the servo controller or the continuous optimal controller. These engineering controllers were designed for machine systems with precise sensors, consistent actuators, short time delays and fast computers. Quite the opposite is true for the human movement system that is characterized by long neuromuscular delays, variability, history dependence and fatigue. Serial ballistic control offers an alternative control paradigm in which smooth control proceeds as a sequence of sub-movements each planned using current sensory information but then intermittently executed âopen loopâ. In the current study we are the first to formally identify refractoriness, a behavioural characteristic that discriminates intermittent (serial ballistic) from continuous control, in the domain of sustained (non-discrete) control of first and second order systems providing definite evidence for the validity of intermittent open-loop control as a paradigm for sustained human control.

[18] Cornelis van de Kamp, Peter Gawthrop, Henrik Gollee, Martin Lakie, and Ian David Loram. Interfacing sensory input with motor output: does the control architecture converge to a serial process along a single channel? *Frontiers in Computational Neuroscience*, 7(55), 2013. [bib | DOI]

Modular organisation in control architecture may underlie the versatility of human motor control; but the nature of the interface relating sensory input through task-selection in the space of performance variables to control actions in the space of the elemental variables is currently unknown. Our central question is whether the control architecture converges to a serial process along a single channel? In discrete reaction time experiments, psychologists have firmly associated a serial single channel hypothesis with refractoriness and response selection (psychological refractory period). Recently, we developed a methodology and evidence identifying refractoriness in sustained control of an external single degree-of-freedom system. We hypothesise that multi-segmental whole-body control also shows refractoriness. Eight participants controlled their whole body to ensure a head marker tracked a target as fast and accurately as possible. Analysis showed enhanced delays in response to stimuli with close temporal proximity to the preceding stimulus. Consistent with our preceding work, this evidence is incompatible with control as a linear time invariant process. This evidence is consistent with a single-channel serial ballistic process within the intermittent control paradigm with an intermittent interval of around 0.5 s. A control architecture reproducing intentional human movement control must reproduce refractoriness. Intermittent control is designed to provide computational time for an online optimisation process and is appropriate for flexible adaptive control. For human motor control we suggest that parallel sensory input converges to a serial, single channel process involving planning, selection and temporal inhibition of alternative responses prior to low dimensional motor output. Such design could aid robots to reproduce the flexibility of human control.

[19] Peter Gawthrop, Kwee-Yum Lee, Mark Halaki, and Nicholas O'Dwyer. Human stick balancing: an intermittent control explanation. *Biological Cybernetics*, 107(6):637--652, 2013. Published online: 13th August 2013. [bib | DOI]

There are two issues in balancing a stick pivoting on a finger tip (or mechanically on a moving cart): maintaining the stick angle near to vertical and maintaining the horizontal position within the bounds of reach or cart track. The (linearised) dynamics of the angle are second order (although driven by pivot acceleration), and so, as in human standing, control of the angle is not, by itself very difficult. However, once the angle is under control, the position dynamics are, in general, fourth order. This makes control quite difficult for humans (and even an engineering control system requires careful design). Recently, three of the authors have experimentally demonstrated that humans control the stick angle in a special way: the closed-loop inverted pendulum behaves as a non-inverted pendulum with a virtual pivot somewhere between the stick centre and tip and with increased gravity. Moreover, they suggest that the virtual pivot lies at the radius of gyration (about the mass centre) above the mass centre. This paper gives a continuous-time control-theoretical interpretation of the virtual-pendulum approach. In particular, by using a novel cascade control structure, it is shown that the horizontal control of the virtual pivot becomes a second-order problem which is much easier to solve than the generic fourth-order problem. Hence, the use of the virtual pivot approach allows the control problem to be perceived by the subject as two separate second-order problems rather than a single fourth-order problem, and the control problem is therefore simplified. The theoretical predictions are verified using the data previously presented by three of the authors and analysed using a standard parameter estimation method. The experimental data indicate that although all subjects adopt the virtual pivot approach, the less expert subjects exhibit larger amplitude angular motion and poorly controlled translational motion. It is known that human control systems are delayed and intermittent, and therefore, the continuous-time strategy cannot be correct. However, the model of intermittent control used in this paper is based on the virtual pivot continuous-time control scheme, handles time delays and moreover masquerades as the underlying continuous-time controller. In addition, the event-driven properties of intermittent control can explain experimentally observed variability.

[20] Peter Gawthrop, Ian Loram, Henrik Gollee, and Martin Lakie. Intermittent control models of human standing: similarities and differences. *Biological Cybernetics*, 108(2):159--168, 2014. Published online 6th February 2014. [bib | DOI]

Two architectures of intermittent control are compared and contrasted in the context of the single inverted pendulum model often used for describing standing in humans. The architectures are similar insofar as they use periods of open-loop control punctuated by switching events when crossing a switching surface to keep the system state trajectories close to trajectories leading to equilibrium. The architectures differ in two significant ways. Firstly, in one case, the open-loop control trajectory is generated by a system-matched hold, and in the other case, the open-loop control signal is zero. Secondly, prediction is used in one case but not the other. The former difference is examined in this paper. The zero control alternative leads to periodic oscillations associated with limit cycles; whereas the system-matched control alternative gives trajectories (including homoclinic orbits) which contain the equilibrium point and do not have oscillatory behaviour. Despite this difference in behaviour, it is further shown that behaviour can appear similar when either the system is perturbed by additive noise or the system-matched trajectory generation is perturbed. The purpose of the research is to come to a common approach for understanding the theoretical properties of the two alternatives with the twin aims of choosing which provides the best explanation of current experimental data (which may not, by itself, distinguish beween the two alternatives) and suggesting future experiments to distinguish beween the two alternatives.

Keywords: Intermittent control; Predictive control; Human balancing; Quiet standing

[21] Ian D. Loram, Cornelis van de Kamp, Martin Lakie, Henrik Gollee, and Peter J Gawthrop. Does the motor system need intermittent control? *Exercise and Sport Sciences Reviews*, 42(3):117--125, July 2014. Published online 9 May 2014. [bib | DOI]

Explanation of motor control is dominated by continuous neurophysiological pathways (e.g. trans-cortical, spinal) and the continuous control paradigm. Using new theoretical development, methodology and evidence, we propose intermittent control, which incorporates a serial ballistic process within the main feedback loop, provides a more general and more accurate paradigm necessary to explain attributes highly advantageous for competitive survival and performance.

[22] Peter Gawthrop, Henrik Gollee, and Ian Loram. Intermittent control in man and machine. In Marek Miskowicz, editor, *Event-Based Control and Signal Processing*, Embedded Systems, chapter 14, pages 281--350. CRC Press, Nov 2015. Available at arXiv:1407.3543. [bib | DOI | arXiv]

It is now over 70 years since Kenneth J. Craik postulated that human control systems behave in an intermittent, rather than a continuous, fashion. This chapter provides a mathematical model of event-driven intermittent control, examines how this model explains some phenomena related to human motion control, and presents some experimental evidence for intermittency. Some new material related to constrained multivariable intermittent control is presented in the context of human standing, and some new material related to adaptive intermittent control is presented in the context of human balance and reaching. We believe that the ideas presented here in a physiological context will also prove to be useful in an engineering context.

[23] Henrik Gollee, Peter J. Gawthrop, Martin Lakie, and Ian D. Loram. Visuo-manual tracking: does intermittent control with aperiodic sampling explain linear power and non-linear remnant without sensorimotor noise? *The Journal of Physiology*, 595(21):6751--6770, 2017. [bib | DOI]

The human operator is described adequately by linear translation of sensory input to motor output. Motor output also always includes a non-linear remnant resulting from random sensorimotor noise from multiple sources, and non-linear input transformations, for example thresholds or refractory periods. Recent evidence showed that manual tracking incurs substantial, serial, refractoriness (insensitivity to sensory information of 350 and 550Â ms for 1st and 2nd order systems respectively). Our two questions are: (i) What are the comparative merits of explaining the non-linear remnant using noise or non-linear transformations? (ii) Can non-linear transformations represent serial motor decision making within the sensorimotor feedback loop intrinsic to tracking? Twelve participants (instructed to act in three prescribed ways) manually controlled two systems (1st and 2nd order) subject to a periodic multi-sine disturbance. Joystick power was analysed using three models, continuous-linear-control (CC), continuous-linear-control with calculated noise spectrum (CCN), and intermittent control with aperiodic sampling triggered by prediction error thresholds (IC). Unlike the linear mechanism, the intermittent control mechanism explained the majority of total power (linear and remnant) (77â87 vs. 8â48, IC vs. CC). Between conditions, IC used thresholds and distributions of open loop intervals consistent with, respectively, instructions and previous measured, model independent values; whereas CCN required changes in noise spectrum deviating from broadband, signal dependent noise. We conclude that manual tracking uses open loop predictive control with aperiodic sampling. Because aperiodic sampling is inherent to serial decision making within previously identified, specific frontal, striatal and parietal networks we suggest that these structures are intimately involved in visuo-manual tracking.

Keywords: motor control, intermittent control, variability

[24] P. J. Gawthrop. Sensitivity Properties of Intermittent Control. *ArXiv e-prints*, May 2017. Available at arXiv:1705.08228. [bib | arXiv]

Keywords: Computer Science - Systems and Control, Quantitative Biology - Quantitative Methods

[25] Peter Gawthrop, Henrik Gollee, Martin Lakie, and Ian D. Loram. Intermittent control of movement and balance. In Dieter Jaeger and Ranu Jung, editors, *Encyclopedia of Computational Neuroscience*, pages 1--6. Springer New York, New York, NY, 2020. [bib | DOI]

[26] Ian Loram, Henrik Gollee, Cornelis van de Kamp, and Peter Gawthrop. Is intermittent control the source of the non-linear oscillatory component (0.2-2Hz) in human balance control? *IEEE Transactions on Biomedical Engineering*, pages 1--1, 2022. [bib | DOI]

[27] J Alberto Ãlvarez MartÃ-n, Henrik Gollee, and Peter J Gawthrop. Event-driven adaptive intermittent control applied to a rotational pendulum. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 237(6):1000--1014, 2023. [bib | DOI]

Intermittent control combines open-loop trajectories with feedback at discrete time instances determined by events. Among other applications, it has recently been used to model quiet standing in humans where the system was assumed to be time-invariant. This article expands this work to the time-variant case by introducing an adaptive intermittent controller that exploits the well-known self-tuning architecture of adaptive control with a Kalman filter to perform online state and parameter estimation. Simulation and experimental results using a rotational inverted pendulum show advantages of the intermittent controllers compared to continuous feedback control since the former can provide persistent excitation due to their internal triggering mechanism, even when no external reference changes or disturbances are applied. Moreover, the results show that the event thresholds of intermittent control can be used to adjust the degree of responsiveness of the adaptation in the system, becoming a tool to balance the trade-off between steady-state performance and flexibility against parametric changes, addressing the stabilityâplasticity dilemma of adaptation and learning in control.
