WOLF FOUNDATION

Michael Berry (standing) and Yakir Aharonov during the 1998 Wolf Prize awarding ceremony in the Chagall hall of the Israeli *Knesset*.

that would seem to be a daunting challenge, but he did connect successfully with a general audience.

The two keynote talks were given by the celebrants. Berry spoke of the interplay between the Aharonov–Bohm effect and the geometric phase in the motion of magnetic half-fluxons in a cloud of electric charges. Aharonov and co-workers had analysed such a problem in the past through qualitative insights. Berry's mathematics allowed him to discover remarkable new features, which he named the 'dance of degeneracies' after the intriguing motions of the topological singularities in the wave functions.

The last talk, by Aharonov, had an unusual format for such a meeting. He presented his ideas about measurement in quantum mechanics by challenging the audience with a paradox involving apparent non-conservation of momentum and inviting discussion. Berry picked up the mathematical subtlety of the paradox and a lively discussion ensued with the audience refusing to leave until the session was extended for half an hour. Aharonov's resolution of the paradox was complete uncertainty of the modular momentum. In his interpretation, the indeterminacies of quantum mechanics are in fact necessary to preserve causality in the measurement process.

The paradoxes, physical and mathematical insights, and experimental achievements reported at the meeting were perhaps best described in the words of Michael Berry, who called the meeting "intellectually delicious".❐

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NEURAL CONTROL

Chaos control sets the pace

Even simple creatures, such as cockroaches, are capable of complex responses to changes in their environment. But robots usually require complicated dedicated control circuits to perform just a single action. Chaos control theory could allow simpler control strategies to realize more complex behaviour.

Eckehard Schöll

Chaos is usually associated with undesirable disorder. In mathematics, chaos is the behaviour shown by any nonlinear dynamic system whose time evolution depends sensitively on its initial conditions, rendering prediction of its future state practically impossible even though it is strictly deterministic. And so it would seem counterintuitive to use chaos to generate well-structured ordered behaviour as needed in robotic control. Yet, writing in *Nature Physics*[1], that is essentially what Steingrube and colleagues describe, in a report that shows that a relatively simple control algorithm based on chaotic behaviour can permit a hexapod (six-legged) robot to exhibit a complex array of adaptive behaviours that allow it to successfully navigate its way through a disordered and changing environment.

A key concept in chaos theory is that of a chaotic attractor. The building blocks of a chaotic attractor (such as the Rössler attractor represented in Fig. 1a) in a system's phase space are formed by many unstable periodic orbits of different periods. The time trajectories wander erratically between these different unstable solutions, which gives an intuitive picture of chaotic motion. At the same time this opens the possibility of generating different kinds of ordered behaviour from chaos by stabilizing any one of these unstable periodic orbits by a small self-adaptable control force, which perturbs the neighbourhood of those unstable orbits such that they become attractive, that is, stable, and without changing the orbits themselves. This is the essence of chaos control.

One of the simplest implementations of chaos control uses time-delayed feedback. This involves a control signal, $u(t)$, that is proportional to the difference in the value of some output variable, $y(t)$, at the present time, t, and some time, $t-p$, in the past, where p is the delay time. That is, $u(t) = K(y(t)-y(t-p))$, where K is a coefficient that determines the feedback strength (see Fig. 1a). Choosing the value of p, so that it is the same as the period of some desired unstable periodic state, one can stabilize this state for suitable values

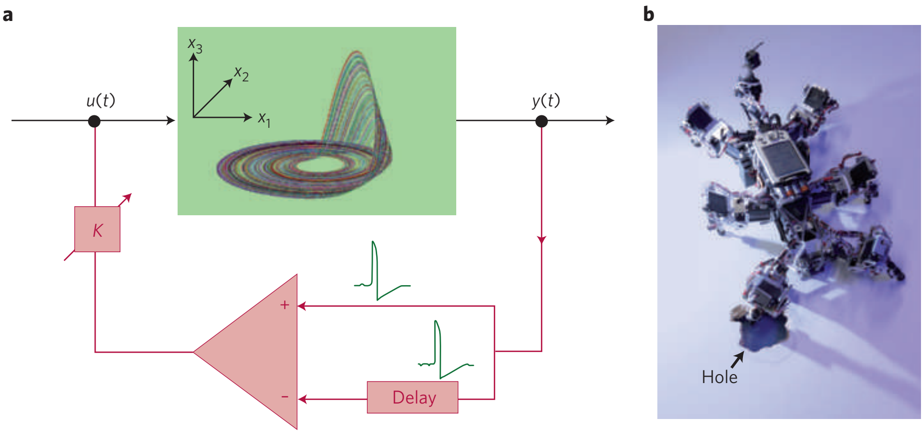

Figure 1 | Chaos control enables a relatively rudimentary neural network to produce complex self-organized behaviour in response to changes in a robot's environment. **a**, Time-delayed feedback control (closed-loop control) of a dynamic system represented symbolically by a chaotic attractor (spiral-type chaotic trajectories in the x_1–x_2–x_3 phase space of the system). The difference between the output variable $y(t)$ and its delayed value is fed back as a control signal $u(t)$, to suppress the chaos and stabilize a single periodic cycle. The value of K determines the strength of the feedback. **b**, When the hexapod is presented with an obstacle, such as one of its legs getting caught in a hole, its chaos-driven neural circuit generates an omnidirectional search pattern to identify an appropriate strategy to overcome the obstacle. Image courtesy of Poramate Manoonpong and Marc Timme, Max Planck Institute for Dynamics and Self-Organization and University of Göttingen.

of the control amplitude, K. This control is non-invasive as the control force vanishes if the target state is reached, so that $u = 0$ if $y(t) = y(t{-}p)$. Moreover, detailed knowledge of the target state is not required, and the scheme is very robust and universal to apply.

Steingrube and co-workers take a similar approach to enable an autonomous robot to select which of several different walking patterns to use in order to navigate through different environments. At the heart of the robot's control system is a simple two-artificial-neuron module represented by a nonlinear (sigmoid) activation function. A time-delayed feedback loop is connected to this chaotic two-neuron module in the same way as shown in Fig. 1a. Each p is associated with a certain gait, and K represents a self-adaptable control strength. The goal is to generate different gaits of a hexapod in an adaptive way, and at the same time to coordinate walking with other types of behaviour, such as orienting. This is achieved by adaptively learning a suitable connection of the multiple sensory inputs with p. The versatility of the time-delayed feedback control method is used in an intriguing way to coordinate several sensory input signals by synaptic learning, and generate different patterns for goal-directed locomotion. The robot learns to escape danger from behind (if approached by a predator) or learns to untrap itself when one of its legs falls into a hole in the ground (Fig. 1b). For instance, the uncontrolled chaotic dynamics — the ground state[2] of the simple neuron module — is used to generate an omnidirectional search pattern for self-untrapping.

This combination of chaos control theory, neural network dynamics and robotics is both new and clever. Indeed, it is remarkable that the authors manage to stabilize a fairly large number of different higher-order unstable orbits of various periods, a feature that is normally not easy to achieve by standard time-delayed feedback control methods. This might be because of the particularly simple form of the neural dynamics in terms of coupled discrete maps, and will need further investigation in the future. This feature is an important ingredient for generating multi-input–multi-output patterns.

How can this robot learn to react optimally to its environment? This is another interesting aspect of the work by Steingrube and co-workers: the optimum feedback strength K is not chosen as a fixed value, but is persistently adapted during the time evolution by comparing the control strength to a measure of the error, that is, the deviation of the present system state from the periodic target state. This is a first step towards combining tools from two different control concepts, chaos control and optimal control, which have been developed by separate scientific communities with little overlap so far. Classical optimal control theory uses a 'cost functional', which is optimized to approximate a desired state with the least 'cost'. It is not yet well understood how the two approaches can be combined, and more research in this direction in the future is necessary.

The results offer important perspectives of applications to a wide range of complex robotic control problems. One may think of using such autonomous robots to explore other planets in space, or to access dangerous sites in case of catastrophes, such as earthquakes or terrorist attacks. Besides locomotion, self-adaptation by chaos control techniques might also be used for self-organized learning of any complex robotic functions requiring multiple inputs and outputs.

Not only does it represent a simple and efficient approach to robotic control, it also provides possible insights into how natural neuronal systems might coordinate complex functions. Ever since the initial suggestion to use time-delayed feedback to suppress chaos[3], the notion of chaos control has been extended to a much wider class of problems involving the stabilization of unstable periodic or stationary states in general nonlinear dynamic systems, including spatiotemporal patterns and stochastic and noise-mediated structures[4]. Therefore, in a broader context, this control approach demonstrates that it could have many cross-disciplinary uses. To mention but a few examples from neuroscience, for instance, time-delayed feedback can be used to suppress pathological states of synchronous firing of neurons, which occur in Parkinson's disease, essential tremor, or epilepsy[5,6]. Also, one might apply time-delayed feedback control to suppress excitation waves (spreading depression) that occur in the brain during a stroke[7] or migraine[8]. In case of a migraine, such feedback loops might perhaps be implemented through special spectacles by using the intensity of light that patients are exposed to as a control variable to which migraine sufferers are particularly susceptible[9]. ❐

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