# Breaking the Sensorimotor Loop – A Memristor-Ready Robot Control Architecture

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***Abstract*—Traditional sensorimotor loops are causal, i.e., the underlying control algorithm exhibits separate input and output lines, where the output fully depends on the input and an internal state of the algorithm itself. This is both true for digital and analog implementations. In the paper at hand we propose an acausal cellular analog architecture for robot control which offers advantages when memristors are to be incorporated for behavior switching and adaptation. Even for complex behavior, e.g., a robot standing-up, the architecture can stay simple since no cross-connections between the different joints' motor control units are needed.**

***Index Terms*—cellular architecture, sensorimotor adaptation, robot control**

## I. INTRODUCTION

Since the widespread use of embedded microcontrollers for the behavior control of robots, control paradigms are traditionally implemented as so-called sensorimotor loops, as shown in Fig. 1 (left): Sensor values are pre-processed, converted from the analog into the digital domain, entering the control paradigm, which is most often written in C, and the resulting values are finally converted back to produce analog voltages/currents to drive the motors, e.g., using pulse-width modulated signals driving H-bridges. The loop is closed via the interaction with the environment.

Even if the control paradigm is fully realized as analog circuit, the causal topology is maintained. High impedance inputs and low impedance outputs can be interconnected without mutual interaction, so the divide-and-conquer principle of engineering can be applied to design the control structure.

Also, hybrid architectures exist, where PID-control is built using operational amplifiers while the parameter settings are controlled by a microcontrolled, e.g., via multiplying digital-to-analog-converters. If memristors are incorporated to build adaptive control paradigms then most often they are multiplexed between normal operation (within a PID-circuit) and write-operations, where the internal state of the memristor is changed using a burst of pulses, generated by a completely different circuit. A representative example is described in [1].

In contrast, the bodily interaction between biological beings and their environment can not always be clearly split into sensing and motor driving: Two people walking hand in hand use an intermediate impedance in their physical coupling. The muscle fibres *exert and sense* forces at the same time.

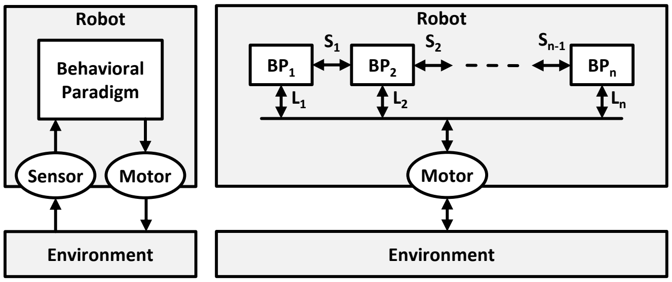

Fig. 1. Comparison of robot control architectures: (left) The classical sensorimotor loop is causal with separate input and output connections. (right) The proposed design uses the motor as sensor, resulting in a fully bidirectional architecture with mutual couplings between the modules and the motor.

## II. BREAKING THE SENSORIMOTOR LOOP

In close analogy to the aforementioned biological *exert-and-sense-forces* ability of muscle fibres, we propose a fully analog system architecture for the control of robot behavior – from simple balancing tasks to more complex motion sequences, like standing up or pushing away objects.

The overall topology is shown in Fig. 1 (right). The motor also functions as sensor, which has several advantages. Firstly, robot design is easy since no additional sensors need to be incorporated into the robot's body nor connected electronically, which reduces the chance of system failure due to broken wires. Secondly, no calibration between sensor and motor voltages is needed since the voltage-to-speed-ratio is the same for driving the motor and for reading back the generator voltage as sensor value. Of course this can be done either in a switched-mode or (preferably) completely without the notion of separate sensor and motor values.

The behavioral paradigms denoted with $\mathrm{BP}_1 \ldots \mathrm{BP}_\mathrm{n}$ are "one hot", i.e., at any given time always only one paradigm $\mathrm{BP}_\mathrm{i}$ is actively controlling the robot's behavior via the corresponding link $\mathrm{L}_\mathrm{i}$. However, all others can still listen to the line and eventually decide to take over sensorimotor control. Optional lateral connections $\mathrm{S}_1 \ldots \mathrm{S}_\mathrm{n-1}$ can be included to allow for

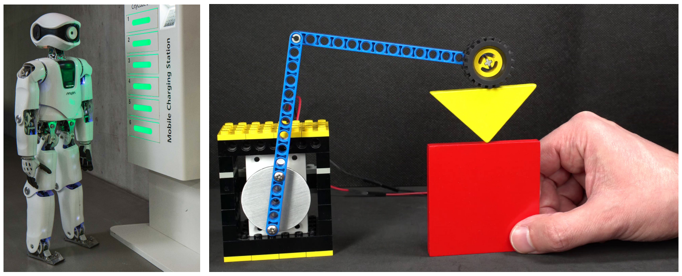

Fig. 2. Various behavioral paradigms have already successfully been tested both on a kid-sized humanoid robot (left), and with small motors (right) the kind of which are used in robotic hands. The fully analog circuitry is able to successfully balance the yellow triangle on top of the red square – even if the latter is moved left and right manually. Although the motor includes a gear and the passive LEGO-joint at the top is quite wobbly, the circuit is still able to detect the slightest touch without additional sensors. A comprehensive video demonstration is available in [3].

entrenched behavior sequences. All links $L_i$ and connections $S_j$ can either be realized as analog CMOS-switches or by using memristors, thus, combining the decision to be active and the sensorimotor connection itself within a single component.

## III. PROOF OF CONCEPT

At first glance it may seem impossible to achieve anything but the most simple behavior using the proposed architecture. But as could already be shown, even a single behavior paradigm built by an analog circuit that consists of only four to ten off-the-shelf components (resistors, capacitors, diodes, and operational amplifiers or transistors) can exhibit rich nontrivial behavior sequences. Fig. 2 (right) shows a kinematic chain with four joints, only one of which is driven by a single motor that is connected to a behavior paradigm implemented as described above. The circuit details are given in [2] and a video demonstration of a behavioral interaction between the robotic device and a human hand is available in [3].

As has been shown in [4], similar behavior paradigms can successfully control a kid-sized humanoid robot to stand upright and counterbalance external disturbances. This is achieved without acceleration sensors, gyroscopes, and the like. At this point it should also be noted that there is one control architecture implemented at each joint – without any coupling between them, except the mechanical coupling through the forces within the robots' body and between the robot and the environment.

More complex behavior sequences are illustrated and analyzed in [5], e.g., a robot is dynamically swinging with an obstacle on top, and after falling over and being captured the robot succeeds to break free and stand up again. Finally, [6] reports how an internal representation of the outer world can be successively built, based upon a simple heuristic which switches between three behavioral paradigms. This is an example for the use of the lateral connections.

## IV. OUTLOOK: INCORPORATING MEMRISTORS

There are at least three different places within the proposed robot control architecture where memristors can be used.

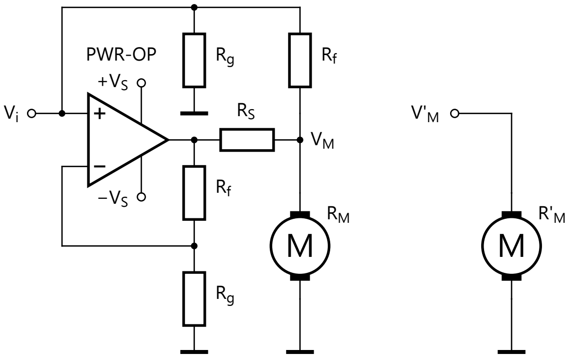

Fig. 3. Impedance adapter to be used between the motor and the bus which all behavior paradigms are connected to (see Fig. 1, right). The simplified equivalent circuit consists of a motor which appears to have a much higher winding resistance and a much lower generator voltage. The resistor ratios can be chosen such that the recommended voltage and current ranges of different memristor types are met.

Firstly, the links between the motor and the behavior paradims can be opened and closed by exceeding resp. falling below memristor-specific voltage thresholds. Secondly, the principle can be applied to the lateral connections between behavior paradigms, thus, sequences useful for learning are realizable.

Thirdly, memristors are helpful to equip behavior paradigms with adaptivity. Early results can be found in [7] and [8], where the authors describe a circuit which is able to lift an robotic arm to the top whilst at the same time improving the efficacy each time the movement is done again. A thorough theoretical analysis is also given.

Using the circuit shown in Fig. 3, any given motor can be adapted to the recommended voltage and current ranges of different memristor types. This allows system designers to pick the memristor type with the most appropriate dynamical properties for the design goal at hand.

Further work will focus on the design of a working prototype which combines a few behavior paradigms, for which funcional circuits already exist, and memristic switching and adaptation within the proposed robot control architecture.

## REFERENCES

[1] B. Chen, H. Yang, B. Song, D. Meng, X. Yan, Y. Li, Y. Wang, P. Hu, T.-H. Ou, M. Barnell, Q. Wu, H. Wang, and W. Wu, "A memrister-based hybrid analog-digital computing platform for mobile robotics," Science Robotics, vol. 5, 2020.

[2] M. Hild, B. Panreck, S. Untergasser, and Maximilian Tolksdorf, "An adaptive balancing robot with exceptional touch sensitivity driven by an analog sensorimotor loop," unpublished.

[3] M. Hild, "Aufstehendes Roboterbein mit CSL," 2021. [Online]. Available: https://www.youtube.com/watch?v=RI8lwfVlQvI.

[4] M. Kubisch, C. Benckendorff, and M. Hild, "Balance recovery of a humanoid robot using cognitive sensorimotor loops (CSLs)," Proc. of the 14th Int. Conf. on Climbing and Walking Robots (CLAWAR), 2011.

[5] M. Hild, "Defying gravity – A minimal cognitive sensorimotor loop which makes robots with arbitrary morphologies stand up," Proc. of the 11th Int. Conf. on Accomplishments in Electrical and Mechanical Engineering and Information Technology (DEMI), 2013.

[6] M. Hild, and M. Kubisch, "Self-exploration of autonomous robots using attractor-based behavior control and ABC-learning," Proc. of the 11th Scandinavian Conference on Artificial Intelligence (SCAI), 2011.

[7] A. Ascoli, D. Baumann, R. Tetzlaff, L. Chua, and M. Hild, "Memristor-enhanced humanoid robot control system–Part I: Theory behind the novel memcomputing paradigm," International Journal of Circuit Theory and Applications, vol. 46 (1), pp. 155–183, 2018.

[8] D. Baumann, A. Ascoli, R. Tetzlaff, L. Chua, and M. Hild, "Memristor-enhanced humanoid robot control system–Part II: Circuit theoretic model and performance analysis," International Journal of Circuit Theory and Applications, vol. 46 (1), pp. 184–220, 2018.