An adaptive balancing robot with exceptional touch sensitivity driven by an analog sensorimotor loop

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1 Introduction

When engineers design robots that are expected to react to touch they tend to use touch sensors attached to the robots' body parts, like fingertips, feet, and the like. This design decision comes at a cost: Additional hardware needs to be integrated or attached (screwed or glued to the robot's surface), additional wiring is necessary, and the underlying circuitry gets more complex.
In contrast, single-cell biological systems, e.g. the amoeba, use their membrane to both sense the environment and motorically interact with it. In this paper we present a simple analog circuit, consisting of only a few, cheap components, which equips a geared DC motor and everything that is mechanically connected to it with exceptional touch sensitivity. The system is able to balance a triangle on its tip while at the same time adapting to lateral shifts of the underlying surface, as shown in Figure 1 and demonstrated live in [1].

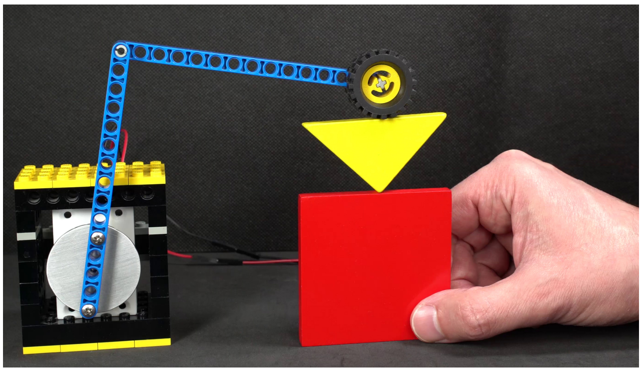

Figure 1: The simple circuit described in this paper is able to successfully balance the yellow triangle on top of the red square – even if the latter is moved left and right manually. Although the motor includes a gear and the passive LEGO-joint at the top is quite wobbly, the circuit is still able to detect the slightest touch without additional sensors. A comprehensive video demonstration is available in [1].

2 Analog Sensorimotor Loop (ASL)

The basic principle is a fully self-referential control loop which is missing the input of a target value (in classical control theory also known as setpoint). This principle has been introduced as so-called Cognitive Sensorimotor Loop (CSL) in [2], although in the digital domain, i.e., using quantized values and a time-discrete model. In this short paper we will neither repeat the digital control loop formulae, nor discuss cognitive aspects of the resulting behavior but rather focus on the new, time-continuous version. Nonetheless, we want to point out that the aforementioned original paper also extends the sensorimotor loop with a learning rule which enables robots to self-explore their behavioral abilities.

2.1 Overall system structure

Before diving into the circuit details, we examine the overall experimental structure, consisting of an energy source (E), the ASL circuit itself, a DC motor (MOT), a gear (G), an robotic arm (ARM, including a passive joint in this example), and the environment (ENV), e.g. a wooden triangle on a moving surface. These components are interconnected as follows:

$$\mathrm{E} \longleftrightarrow \mathrm{ASL} \longleftrightarrow \mathrm{MOT} \longleftrightarrow \mathrm{G} \longleftrightarrow \mathrm{ARM} \longleftrightarrow \mathrm{ENV}$$

As can be seen, in the analog domain and without an additional sensor we no longer have a sensorimotor *loop*, but rather a sensorimotor *bidirectional pathway* instead. Also, due to the time-continuous operation, the split into sensor and motor pathways is dissolved.
The ASL mediates the flow of energy between each neighbouring components in both directions, while the form of energy changes along the path: From electrical to magnetical to mechanical, and all the way back. It is remarkable that the complete system works very smoothly, sensitive, and highly reactive – despite the fact that there are many highly non-linear energy losses along the pathway in both directions, namely friction, backlash, and looseness of the passive plastic joint (see Figure 1).

2.2 Behavioral modes of the ASL

When an external force is applied from the environment to the robot's arm, e.g. through human touch or through the earth's gravitation, the induced energy enters the ASL circuit and there are basically two different responses possible: Either the energy is consumed, so the robot's arm surrenders to the external force and *follows along*, or energy is sent back to oppose the external force and *go against* it. In the case of gravitationally induced action, this will result in self-erecting behavior. As we will shortly see, those two modes can be switched between by the change of a resistance.

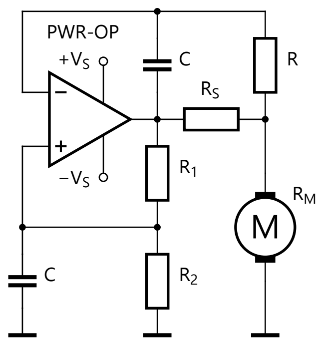

Figure 2: Circuit realizing the analog sensorimotor loop (ASL) described in this paper. Amongst other behavioral tricks, this minimalistic circuit is able to balance very shaky mechanical setups, like the one shown in Figure 1. See text for component values and functional description.

3 Description of the analog circuit

The analog CSL, as shown in Figure 2, is comprised of a power operational amplifier PWR-OP (TCA0372 or L272), two capacitors C (100 nF), a shunt resistor R_S (4.7 Ω, 0.5 W), a resistor R (10 kΩ), and a linear potentiometer (100 kΩ) which, for the sake of better explanation, is shown as the serial resistor pair R_1 and R_2. That is six inexpensive components in total, where still there is a spare opamp available in the IC package.
The energy source is made up of two standard 9 V block batteries, i.e., $+V_S = 9\,V$ and $-V_S = -9\,V$, relative to ground. The geared DC motor (Faulhaber type 2619S012SR 22:1) has an internal resistance of $R_M = 36.5\,\Omega$.

3.1 Circuit topology and time constant

The circuit can be divided into a differential integrator and a Wheatstone bridge. The differential integrator is built around the amplifier PWR-OP, with the negative input path being comprised of R and C, and the positive input path being comprised of the potentiometer ($R_1 + R_2$), and C. The component values have been chosen such that there is a potentiometer position, where at the same time the following holds true:

$$R_1 || R_2 = R, \quad (1)$$
$$R_1 / R_2 = R_S / R_M. \quad (2)$$

This ensures two things: Firstly, the integrator's time constant is the same in both input paths, namely $\tau = RC = 1$ ms with the aforegiven values. Secondly, the Wheatstone bridge consisting of R_1 and R_2 on the one side, and R_S and R_M on the other side (R can be ignored here, since $R \gg R_S$) forwards the same voltages to both the negative and positive input of the differential integrator, as long as the motor stands still, i.e., as long as there is no voltage (back EMF) generated in series with R_M. This is independent of the integrator's output voltage, since the Wheatstone bridge is perfectly balanced. In consequence, as the input voltages to the integrator are the same, the integrator will hold its current output voltage.

3.2 Setting the ASL mode with the potentiometer

To better understand the following, let us assume that there is a simple pendulum arm attached to the motor and that the integrator outputs a constant voltage which is just sufficient enough that the arm is 30 degrees off the neutral hanging position. If we now turn the potentiometer slightly such that R_1 increases, the voltage at the positive input is lower than that at the negative input, so the integrator will slowly reduce its output voltage and the arm sinks down. Cleary, that is the ASL mode where the robot's arm *follows along* with external forces.
Now for the more interesting case: If we slightly turn the potentiometer in the other direction, a constant feedback from the integrator's output to the the positive input is introduced. Thus, the integrator's output voltage rises slowly and so does the pendulum arm – it *goes against* the gravitational force. Once the arm gets nearer to the upright position, it gets increasingly easier for the motor to move, so the motor's generator voltage increases more steeply (as compared to the lower arm position) and thus the voltage at the integrator's negative input dominates the one at the positive input: The integrator's output voltage goes to zero as the arm reaches the fully upright position.
Although the kinematic chain is more complex in the setting shown in Figure 1, the underlying principle still applies. It is the same situation as with the simple pendulum – the only difference being that the rotational point is below the pendulum, at the triangle's tip, on the squares top surface.

4 Biological relevance and conclusion

The presented ASL effectively mimics the reflex loop of muscle spindles: When a muscle lengthens due to an external force, the induced nerve activity increases alpha motor neuron activity which in turn causes the muscles to go against the external force. When a person stands upright and begins to lean to one side, the described sensorimotor response will thus correct the posture. The process of slowly leaning slightly to one side or the other repeats over time, i.e., people never completely stand still. The very same behavior can be observed when the ASL paradigm is used to enable a kid-sized humanoid robot to stand upright, balance its own body and counterbalance external disturbances, as shown in [3]. There, the circuit needs to be implemented one for each joint. Interestingly, no coupling is needed between the ASLs other than the natural physical forces inside the mechanical body (see [4]).

References

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[4] M. Hild. Defying Gravity – A Minimal Cognitive Sensorimotor Loop Which Makes Robots With Arbitrary Morphologies Stand Up. 2013.