# Balance Recovery of a Humanoid Robot Using Cognitive Sensorimotor Loops (CSLs)

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Recovering balance from unknown disturbances can be considered a complex sensorimotor ability of humanoid robots. We present so-called Cognitive Sensorimotor Loops (CSLs), discuss their properties and show how they can be used for motion generation and balance recovery on robots. Their behavioral abilities will be demonstrated on a single robot leg controlled by CSLs and we will show that a complex stand-up motion can emerge from the interplay of independent joint controllers. Furthermore, we explain how CSLs can be used to help a robot to adapt to changing slopes and recover balance after disturbance.

*Keywords*: Balance Recovery, Sensorimotor Control, Humanoid Robots

## 1. Introduction

Balance control is a crucial skill for natural and artificial systems alike. So, in order to accomplish balancing tasks, modern robots possess rich sensory feedback, but their performance still does not reach the robustness of biological individuals. Although the fusion of different sensor modalities may eventually lead to an optimal solution, we try to approach the problem from a different, more minimalist perspective.

In the paper at hand we will extend the notion of Cognitive Sensorimotor Loops (CSLs)[1] and use them for motion creation and balance recovery on the modular humanoid robot *Myon*.[2] For this, the structure is as follows: On the basis of the CSL described in Section 2, we will show how a single robot leg can perform a complex stand-up motion with the use of multiple independent joint controllers (Section 3). Here, we also demonstrate that the CSLs enable a humanoid robot to stabilize its upright standing and recover balance after disturbances, e. g. pushes or changing slopes. In the final section, we give a brief overview on future research.

## 2. Cognitive Sensorimotor Loops (CSLs)

Connecting sensory inputs to motor outputs, which in turn cause perceptible changes in sensory data, is usually termed a closed sensorimotor loop. The basis for our experiments on robot motion is the simple but yet effective structure depicted in Figure 1 (left). It uses the joint angle $\varphi(t)$ as input, and outputs the actuator's driving voltage $u(t)$. The discrete time update rule is given by $u(t) = -g_i\varphi(t) + \left[g_i\varphi(t) + g_f u(t)\right] z^{-1}$ with $u(0) = 0$, where $z^{-1}$ is the unit delay operator. The left half, comprising the input paths $-g_i$, $g_i$ and the unit delay, forms a differentiator with negative sign. Hence, there is no need for absolute sensory values: it is sufficient to provide a velocity signal and remove the lower input pathway. The right half can either function as leaky integrator, ideal integrator, or integrator with additional feedback. Joint angle $\varphi(t)$ and motor input $u(t)$ are supposed to have the same sense of rotation, therefore, if $u(t) > 0$ then the motor accelerates to get $\dot{\varphi}(t) > 0$.

Depending on the parameters $g_i$ and $g_f$, a CSL can operate in different modes which equip a robot with distinct behaviors like contraction and release. We will refer to them as *behavioral modes* (see Table 1 for an overview).

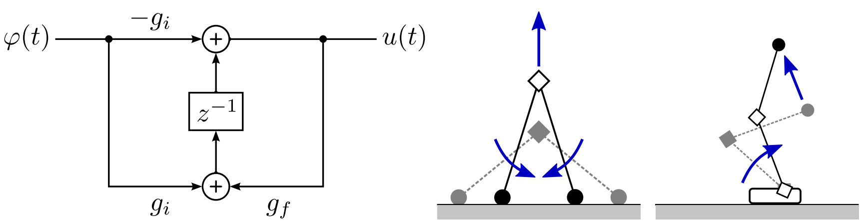


Figure 1. Left: Structure of the CSL. Right: CSL operating in contraction mode for different morphologies which are subjected to gravity.

For example, by setting $g_i$ positive and the feedback to $0 \leq g_f < 1$ the CSL will operate in *release mode*. The actuator's driving voltage is proportional to the negative angular velocity which will slow down the motion, acting as additional fluid friction. On the other hand, if we turn the sign of $g_i$ the control loop will support the current motion. Thereby, the angular velocity is positively fed back.[3]

If we choose to set $g_i > 0$ and $g_f = 1$ the sensorimotor loop will try to hold the current position. Beginning with a steady state, we can think of $u(t)$ as the angular displacement. The CSL henceforth operates like a position controller with the set point put to the last known angular position at rest.

In the following, the behavioral mode of major interest is *contraction mode*. It works against all external forces, e. g. pushes or gravity. For this, the velocity is negatively fed back and further amplified due to the feedback parameter $g_f$ larger than one. See the CSL's behavior for two different morphologies subjected to gravitational forces in Figure 1 (right). A particular property of contraction mode appears when the physical system passes an unstable fixed point, e. g. one can think of an inverted pendulum controlled by CSL which is approaching the upright position. In this case, the velocity and therefore the CSL's output decrease until zero-crossing and finally change the sign. This makes the joint motor turn its rotational direction and eventually stabilize this unstable fixed point.

In contraction mode, the value of $u(t)$ can be used to implicitly detect what is happening to the physical system. When $u(t)$ is almost zero, the physical system is on the transient into a steady state, i. e., an unstable fixed point. Otherwise, if it diverges and tends to grow out of bounds (here: $[+1, -1]$), the physical system is situated in a stall situation while maximally driving its motors. In the same way, the CSL will experience attached loads and can be used to distinguish *up* and *down* while it is actively opposing gravity. That is why we call this sensorimotor loop *cognitive*.

Table 1. Overview of possible behavioral modes. Each parameter configuration exhibits a distinct behavior, see Figure 2 below for illustration.

| Release | Hold Current Position | Contraction | Support Motion |
|---|---|---|---|
| $g_i > 0$<br>$0 \leq g_f < 1$ | $g_i > 0$<br>$g_f = 1$ | $g_i > 0$<br>$g_f > 1$ | $g_i < 0$<br>$g_f = 0$ |

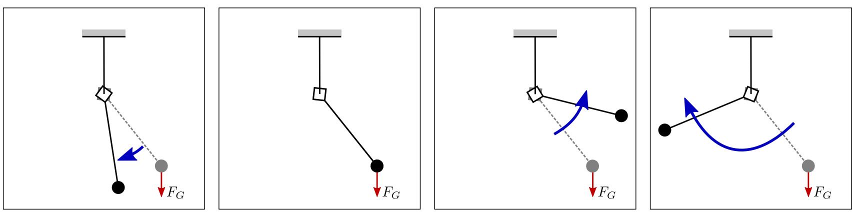


Figure 2. Different behavioral modes of the CSL form nature-like motions; From left to right: release, hold current position, contract, or support an externally induced motion.

The motion of a physical system, e. g. a robot leg, is usually bounded by joint limits. Desirably, these limits should be estimated during self-exploration[1,4–6] and learned for future use. But for now, a simple way to cope with joint limits is to manually identify the maximal angular positions and set the CSL into release mode when a joint limit is reached. Otherwise, the sensorimotor loop in contraction mode will *sense* the mechanical barrier as the direction of maximal resistance and work against it.

## 3. Single Leg Stand-up and Balance Recovery

In what follows, we concentrate on the control of a single leg of the modular humanoid robot Myon with the proposed Cognitive Sensorimotor Loops. Due to the robot's distributed processing nodes and its onboard power supply, a single leg already constitutes a fully autonomous robot. The programming code is deployed onto the robot. Also, there is no further connection to external computers. For the experimental run described below, we only use a fixed set of parameters for the CSLs. When the hip, knee, and ankle joints are each controlled by local CSLs in contraction mode, then a complex behavioral sequence emerges, as outlined in Figures 3 and 4.

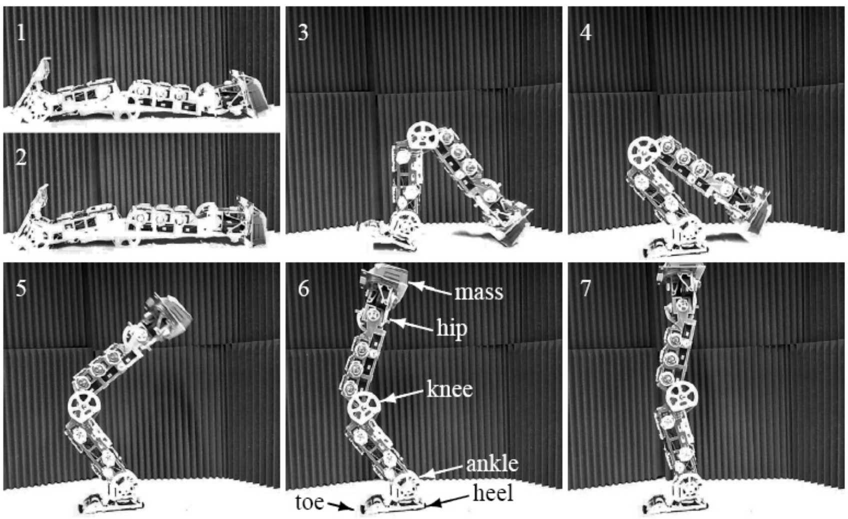


Figure 3. A single leg of the modular humanoid robot Myon standing up using the proposed CSLs. Each of the three joints is locally controlled by a contracting CSL whilst no direct communication takes place between the controllers. Complex behavior emerges from the interplay via momentum.

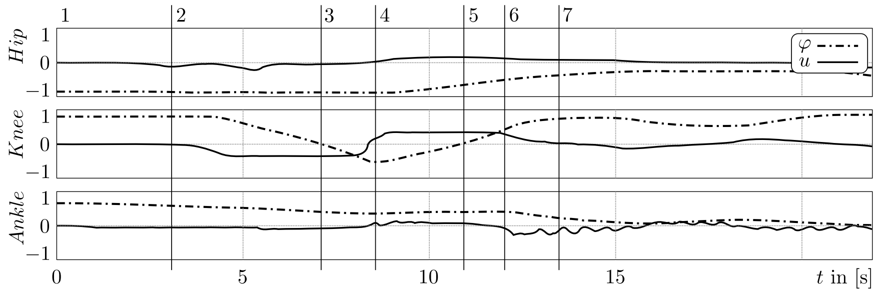


Figure 4. Joint angles of Myon's leg and the control outputs in the stand-up motion. The numbered vertical lines correspond to the snapshots of Figure 3. An experimental run takes about 20 seconds. In the end (7) the leg is never at rest but performs a slight swinging motion in upright position.

First, only ankle, knee, and the mass touch the ground, so the hip joint experiences load and starts to contract (1–2). This lifts the knee from the ground, so the knee joint also starts to contract (3). At some point the leg tilts over onto toe and heel, so that the mass is in the air (4). This makes the knee joint turn its rotational direction, it now works against gravity (5). The other joints are well compensating the forces, so the leg ends up in a fully upright position (6–7) and stays there balancing even if it is pushed or the ground is tilted. In summary, it can be stated that a leg controlled by CSLs is able to stand up and balance without any changes in control, e. g. without switching of target values or adjustment of parameters.

To demonstrate the CSLs' ability to balance more complicated robot morphologies, we did tests with another configuration of Myon as shown in Figure 5 (right). Here, two CSLs are used for the left and right hip roll joint, which are responsible for lateral movements of the legs. When used in contraction mode, the CSLs will create a motion of the legs similar to the one depicted in the middle panel of Figure 1. This enables the robot to successfully recover balance after moderate disturbances of different kinds and also stabilizes its upright posture even when the ground is tilted.

When using contraction mode only, the hip actuators of the two legs will work against each other all the time. This behavior is unintended, once the robot is in a fully upright position and already well balanced. To avoid useless heating-up of the motors we propose crossed inhibitory connections between the two controllers. This is done by modulating the feedback $g_f$, effectively changing one CSL smoothly from contraction to release mode when both operate in opposing directions. For this, the output $u(t)$ is been split into positive and negative parts denoting $u_+(t) = \max(0, u(t))$ and

$u_-(t) = \min(0, u(t))$, which are connected to $i_\pm$ of the other CSL, cf. Figure 5 (left). These inputs inhibit joint contractions either in positive or negative sense of rotation.

Beyond that, it has come to light that for this body configuration even a single driven hip roll joint is sufficient for balancing an upright posture while withstanding gravity and slight disturbances.

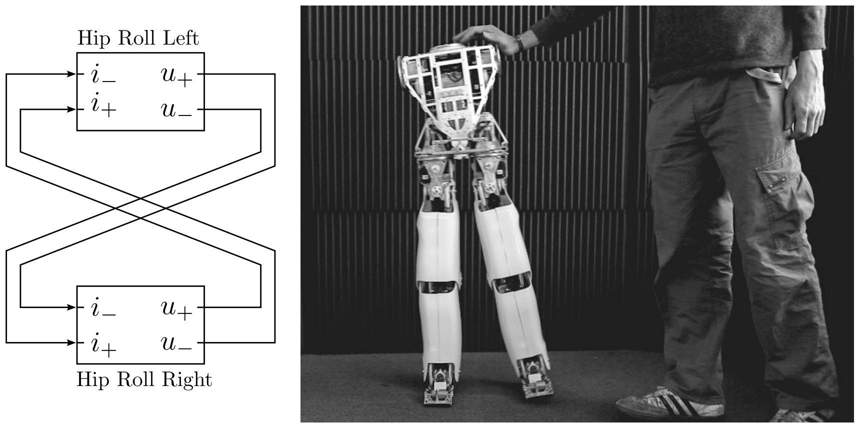


Figure 5. Left: Schematic view of crossed inhibitory connections between two CSLs controlling left and right hip motors of a humanoid robot. Right: Lower body part of Myon during balancing motion. Head and Arms are not attached. Contracting CSLs on the hip joints make the body withstand pushes or adapt its upright posture to tilted grounds.

## 4. Summary and Outlook

We have explained the functional principle of so-called Cognitive Sensorimotor Loops (CSLs) and have shown their benefits for the creation of stand-up motions for humanoid robots. We demonstrated how complex multi-joint motions emerge from the interplay of local joint controllers using a strictly reduced set of sensory values, namely only position and velocity information of each joint and no additional communication between the controllers.

We also approached the problem of balance recovery in a model-free manner and will take the next step to stabilize movements and disturbances within the sagittal plane making use of the arms. Further work will focus on the generation of model-free walking patterns using reactive limit cycle walking methods[7] incorporating the proposed CSLs.

**Acknowledgments**

This work has been partly supported by the European research project ALEAR (FP7, ICT-214856). The authors send special thanks to Mario Weidner for his contributions and suggestions regarding the stand-up of the single Myon leg.

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