Abstract: This chapter aims at providing a basic understanding of the sensorimotor loop as a feedback system. First we will give some insights into the richness of behavior resulting from simple closed loop control structures in a robotic system called the BARREL. This richness is a lesson we can learn from dynamical systems theory: even very simple systems can produce highly complicated behavior. Nearly everything is possible in such a feedback system that is provided with enough energy from outside. Surprisingly, this is accomplished even with extremely simple, fixed controllers, to which we will restrict ourselves here. In later chapters we will see how the homeokinetic principle makes these systems adaptive and drives them towards specific working regimes of moderate complexity, loosely speaking somewhere between order and chaos.

The aim of this chapter is to make the reader familiar with the general structure and specific properties of tightly coupled sensorimotor loops. In these loops the motor commands are directly related to the sensor readings, so that the robot with its “brain” forms a feedback system. In this context the framework of dynamical systems, known from mathematics and physics, started to get increasing attention in the last two decades [13, 81, 120, 152]. It is a powerful method to analyze [75] and construct [39, 72, 78, 81, 152, 160] robot controllers, as it allows one to formulate the time evolution of the system, in a quantitative manner and to obtain both analytical and qualitative predictions. Dynamical system theory also led to the application of chaos control and coupled chaotic oscillators to robotics [91, 138, 159].

After a general introduction of closed loop control, using the framework of dynamical systems, we study a specific example, the BARREL, that is particularly interesting by its strong embodiment effects. The general settings are investigated subsequently in an elementary sensorimotor loop, a one-dimensional system controlled by a single neuron. Without noise, a pitchfork bifurcation occurs and a pronounced hysteresis behavior is established if the neuron has a bias. We introduce our concept of an effective bifurcation point to allow for noise effects. This concept defines a specific working regime, where robots can already take decisions while still being sensitive to perturbations by the environment. Eventually, we present briefly neural networks as universal tools for the realization of the control system. The investigations are based on dynamical systems theory but the mathematics will be kept

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simple and essentially self-contained so that no special knowledge of the latter is necessary.

The theoretical studies are underpinned by robotic experiments that can be executed with our simulation environment. Experiments are provided for studying closed loop control and in particular the concept of the effective bifurcation point under various conditions. The role of the embodiment can be investigated with wheeled robots. When interconnected to form a chain of robots emergent cooperativity is observed even though decentralized control is used. In this way, the present chapter makes first contact to the central idea of externalizing complexity, namely to control complex physical modes with very simple control structures and thus to source the complexity out to the interaction with the environment.

3.1 Sensorimotor Loop — The General Case

In a self-consistent approach to self-organizing robot behavior, the sensor values are the only source of information for the robot. This is also the credo of our approach. The communication between the “brain” and the body of the robot takes place at the discrete instants of time \( t = 0, 1, 2, \ldots \). In practice, typical clock frequencies are ranging from 10 to 100 Hz, depending on the speed of the information processing. In each time step a vector of sensor values \( x_t \in \mathbb{R}^n \) is reported. Let us illustrate this by two examples. Firstly we consider a wheeled robot with sensor vector

\[
x = (v_l, v_r, s_1, \ldots, s_k)^\top
\]

(3.1)

where \( v_l \) and \( v_r \) are the wheel velocities of the left and right wheel, respectively, as measured by the wheel counters, and \( s_i \) are the values of the infrared sensor \( i \) with \( 0 \leq s_i \leq 1 \). The wheel velocities are examples for proprioceptive sensors. Infrared sensors are examples of exteroceptive sensors since they get information about the relation to the outside world. In many of the applications treated further below the robot has only proprioceptive sensors providing informative feedback on the state of its body, an example being our dog robot, see Fig. 3.1, where

\[
x = (x_1, \ldots, x_n)^\top,
\]

(3.2)

\( x_i \) are the joint angles.

3.1.1 The Controller

At each time step \( t \), the controller sends a vector \( y_t \in \mathbb{R}^m \) of target values to the motors of the robot. Closed loop control means that the controller is given by a function \( K: \mathbb{R}^n \to \mathbb{R}^m \) mapping sensor values \( x \in \mathbb{R}^n \) to motor values \( y \in \mathbb{R}^m \). In the most simple case this is a function