Hands-on Exploration of Sensorimotor Loops

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Abstract. The behavior of many living beings is at least partly influenced by the coupling of their sensors and actuators. In order to be able to implement behavior adapted to the environment in robotic systems as well, it is helpful to understand and emulate these sensorimotor couplings. Therefore, sensormotorics is not only a current research topic, but can also be found in robotics curricula. In order to understand this complex topic in depth, first-hand experience of interacting with robots is extremely helpful. In this paper, a curriculum for a sensorimotor lecture is presented, which includes a lot of practical experience. For this purpose, the necessary mathematical basics (dynamical systems) are taught and deepened with experiments on simple robots.

Keywords: cognitive robotics, sensorimotorics, hands-on experiments

1 Introduction

In robotics research, among other things, researchers are working intensively on sensorimotor coupling. This refers to the coupling of sensory stimuli with motor activity in natural and in artificial systems. The sensors provide information about the environment (for example visual stimuli) and about the state of the own body (for example temperature). To survive in an environment, a system must process this information and translate it into actions that satisfy its needs and, if possible, improve its state. Since there is an interdependence, actions performed can influence sensory information and vice versa. This ongoing process is called a sensorimotor loop. To enable robots to interact in our highly complex and unstructured environment, it can be helpful if they, too, have some sort of coupling of their sensors to their actuators. These can be simple wirings from sensors to motors, such as those described in [Braitenberg, 1986], or more complex networks, such as in [Sun et al., 2020]. However, it can be said that the study of sensorimotor couplings is still in its infancy. Therefore, it is important to incorporate the study of sensorimotor couplings into education in relevant topics (such as humanoid robotics in this paper) so that future researchers can be exposed to it at an early stage. However, it is often difficult to teach these complex relationships and the mathematical background in an easily understandable way. In order to still achieve an intuitive understanding among young scientists, this paper presents a concept in which sensorimotor principles can be experienced interactively with the help of increasingly complex robots. Here, students

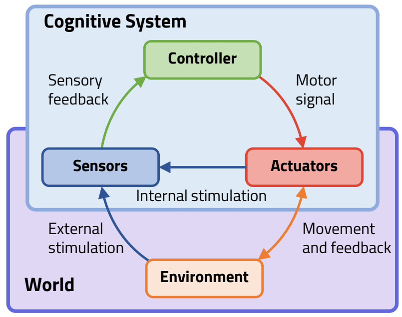

Fig. 1. A cognitive system consisting of sensors, actuators and a controller. It is situated in some environment and interacts with it. The dynamic system of interest comprises the cognitive agent and the world surrounding it. (Figure based on [Montúfar et al., 2015])

are enabled to complement theoretical content with hands-on experiments by interacting with robots, customizing them with their own programming, and conducting their own experiments.

2 Sensomotorics curriculum

In the following, first an overview of topics from the curriculum of the sensorimotor course is given. Afterwards, It is described, how this curriculum is used, the individual topics are put into context and it is argued why they are relevant for robotics.

- Motor Dynamixel XH430
- Dynamical Systems Theory
- Sensorimotor Loops
- Neural Networks
- Artificial Evolution
- Central Pattern Generators etc.

This list of topics comprise the "sensorimotorics" lecture (2. semester) in the program *Humanoid Robotics* at Beuth University of Applied Sciences in Berlin. This lecture continues topics from the first semester (reactive robotics, electronics, mathematics) and prepares for the following semesters (cognitive robotics, adaptive systems, control theory). In the course of this lecture, the students deepen their knowledge using different robots. To do so, they first need to understand how a typical robot actuator works, and how they can use it. So in the first weeks, an important topic is the Dynamixel X430 actuator and how to program it. Equipped with this actuator, different sensorimotor behaviors can be explored. The mathematical tools for sensorimotor systems come from dynamical systems theory. A dynamical system is the mathematical description of a system that changes over time. In most cases, the exact behavior of more complex systems cannot be predicted, but qualitative statements can be made. For example, specific states, called attractors, can be described toward which a system moves (e.g., the resting state of a pendulum). Figure 1 shows a cognitive agent (for example, a robot) embedded in an environment. It interacts with this environment using its actuators and sensors. The environment and the cognitive system, both dynamic systems in their own right, influence each other and therefore also form a dynamic system overall. The controller may consist of a recurrent neural network [Haykin et al., 2009]. These networks are capable of enabling robots to behave in interesting ways (see, for example, [Hülse et al., 2004] or [Candadai et al., 2019]). One can also consider them as dynamical systems and therefore study them with the same mathematical tools. To find suitable networks, it is helpful to use artificial evolution. Following ideas from nature, artificial evolution is a population-based optimization algorithm [Nolfi and Floreano, 2000]. It is often used when classical optimization strategies such as gradient methods do not work well. Artificial evolution can provide a solution to a problem that is not optimal in some cases, but good enough for the task at hand. Instead of evolving neural networks via artificial evolution, one can also find interesting behaviors through theoretical reasoning (see, e.g., [Schilling et al., 2013]). For example, Central Pattern Generators are simple constructs of a few neurons that can serve as the basis of walking behaviors of more complex robots ([Hild, 2008]). Another important topic is the interaction of robots with their environment. To achieve robust behavior in dynamic and unstructured environments, it is necessary for robots to adapt to changing environmental conditions. It can be beneficial if the robot is able to use its body and sensors to acquire the information it needs about the environment to do so. Again, dynamic systems theory can be used to structure the gathered information. For example, stable postures (*lying down*, *standing up straight* see figure 4 for some examples) of the robot correspond to attractors in the dynamic system consisting of robot and environment. In addition, there are unstable postures (repellors, e.g. tilting on an edge). This possibility space can be explored by the robot and paths (i.e. movement patterns) can be found so that the robot can switch between different postures. Depending on the complexity of the robot and the environment, more or less complex sensorimotor manifolds are thus found.

3 Practical exploration of sensorimotor behavior

To give students a feel for how these theoretical topics can be applied to the real world, they are given the opportunity to experiment with a number of robots. To do this, they are given a small box, as shown in Figure 2, which contains a Dynamixel XH430 motor, as well as a battery and connectors. This allows them to connect the motor to a smartphone, as shown on the left side of the figure. First, the teaching content about the motor is described. Then it will be discussed how the robot is programmed and which tools are provided for this purpose. The conclusion is formed by 2 examples of robots that are discussed in the lecture.

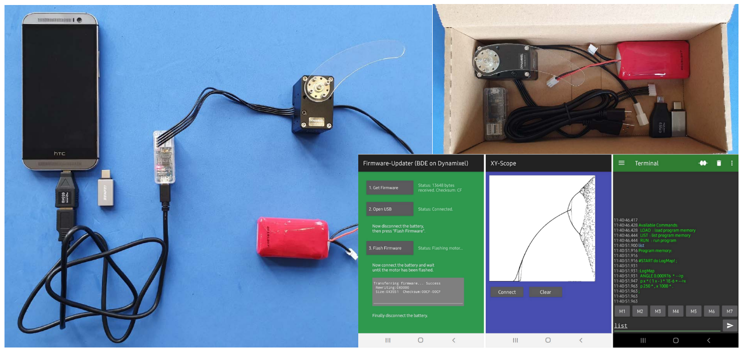

Fig. 2. The box, shown on the right top, includes the motor XH430, a battery and some cables and connectors. Students can connect this system to their smartphones as shown in the left part of the figure. In the right bottom, screenshots of the android apps are shown, which are used to program the motor.

3.1 The Dynamixel Actuator for simple robots

As an example of a robotic actuator, the XH430-W210-R from Dynamixel is discussed in the lecture. This high performance servo is equipped with an STM32 microcontroller and a magnetic rotary encoder. Using the electronic inner workings of this motor, H-bridges, shunt resistance and PWM are explained. This builds on the knowledge students gained in the first semester electronics lectures. Subsequently, students are given the opportunity to conduct experiments with the motor using Android apps. For this purpose, a custom firmware was developed for the actuator. It is based on a specially developed Forth ([Brodie, 2004]) dialect, called *Behavior Design Environment* (BDE). This custom programming language will also be used in later semesters to program larger humanoid robots (there is an extended version of BDE for this purpose). In this language, sensorimotor loops can be programmed with a few simple commands and thus behaviors can be brought to the motor (and later robots). The firmware is flashed on the actuator using an android app, shown on the right bottom of figure 2. The firmware flashing software is shown in green on the left side. In the middle is an app, where motor values can be plotted. In this case, the logistic function is plotted using the motor angle as parameter. So by interacting with the motor, the curve is plotted. This is a first simple example of a dynamical system. On the right side, the corresponding code is shown, by using an android terminal to program the motor. There, the individual BDE programs can be flashed on the motor. Simple sensorimotor loops are developed and programmed in the lectures with the students. The behavior can then be tested in interaction with the motor. An example is the *Cognitive Sensory Motor Loop* (CSL, see [Hild, 2013]), whose flow chart can be seen in Figure 3. This sensorimotor loop has different modi, for example, the contraction mode causes the motor to move against external forces.

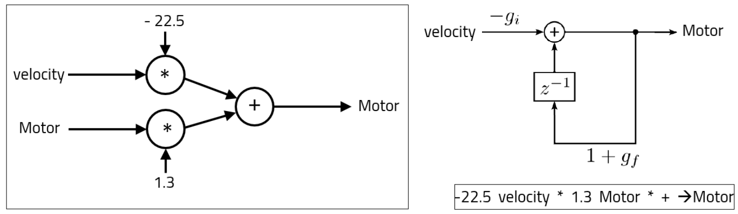

Fig. 3. The cognitive sensorimotor loop [Hild, 2013] as a flow graph. In the right bottom, its implementation in the programming language BDE is shown. The z^{-1} block is a delay of one time step. The coefficients are $g_i = 22.5$ and $g_f = 0.3$.

3.2 An example Robot

With a few additional parts that the students can produce themselves, the first simple robot can be built. One example is shown in Figure 4 on the left. It consists of the XH430 motor described above, the battery from the box, and some molded parts laser cut from acrylic glass. As can be seen in the figure, it is designed so that the axis of the motor always remains parallel to the ground once it has been oriented that way. This allows the state of the robot to be described by four variables. The first two are the angle of the robot to the ground and its derivative. The next two are the current angular position of the motor and its derivative.The states where the robot does not move are the fixed points of the system. The robot postures shown in the right part of figure 4 are instable fix points, where slight perturbations causes the robot to leave the posture. The CSL in contraction mode swaps stable and instable fix points, so that the postures in the figure become stable. The corresponding nodes are connected by arrows when the robot can move from one posture to another. Green arrows mean counterclockwise rotation of the motor, red means clockwise rotation. These transitions are only possible in one direction. Only between postures that are connected with a black arrow (pointing in both directions), the robot can switch between postures by itself. This simple example already shows a rich behavior that can be investigated with the learned methods. To find out, in which posture the robot is, students usually suggest to equip the robot with a sensor (e.g. IMU) to measure the angle between robot and table. But that is not necessary. By choosing a suitable movement, the sensorimotor behavior provides enough relevant information. For example, the motor voltage can be used to find out in which posture the robot is. To see this, experiments are carried out in which joint angle and motor voltage are measured and the robot's postures are recorded. At the respective posture, one can then see the influence of gravity on the motor voltage, as can be seen in Figure 5. In the displayed series of measurements, the robot's motor was kept at a constant rotational speed. During this process, the motor voltage was measured (blue line in the figure). It can be seen that the robot's postures with the same angular positions require different amounts of motor voltage to maintain the speed, depending on whether the robot is standing upright (posture a), or lying on the ground (posture h). Moving from

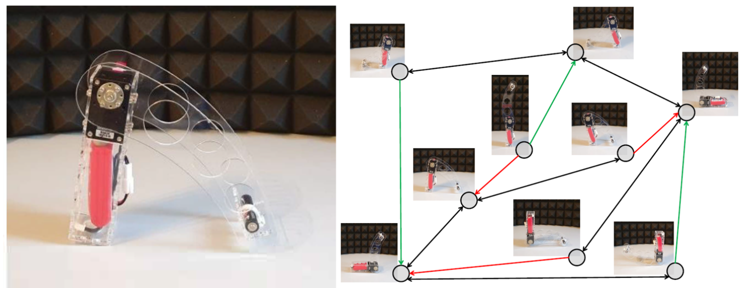

Fig. 4. One design of a simple robot, which can be built with the described motor. The right side shows stable fix points of the system containing the robot, the CSL and the environment, as well as the possible transitions between them (which the robot can do by itself). The green arrows represent counterclockwise rotation of the motor, red means clockwise. Black arrows represent both directions.

posture a to the right, you can see the point where the robot falls over ($\varphi \approx 70$), which is the sharp drop in motor voltage. If the running direction of the motor is reversed here, the robot can no longer come to posture a by itself, hence the motor voltage follows another curve (The ripples in the curve stem from the stick slip effect between robot and table). Without complex sensor technology, the robot can therefore already learn a lot about its environment and its own body. The students now have all the freedom they need to make custom bodies for their robots and to repeat the experiments and gain their own insights. Of course, feeling and understanding the sensorimotor behaviors is also part of the exam for this course. For example, a randomly chosen behavior is set on the robot before the examinee enters the room. Now, as a first task, the behavior (and the sensorimotor loop behind it) should be identified through interaction.

4 Conclusion

Insights on sensorimotor couplings from research on living beings are often useful in robotics. In order to prepare future roboticists, sensorimotorics is being incorporated into various curricula of programs like humanoid robotics. To understand this complex topic in depth, it is useful to interact with the robot and experience the behaviors haptically. In this work, it was presented how in-depth hands-on experiences can be built into a sensorimotor curriculum. For this purpose, the necessary mathematical basics (dynamical systems, neural networks) were deepened with the help of experiments on simple robotic systems. Each student gets a motor with accessories, with which she can try out the learned contents in practice. Android apps were developed to be able to program the motor. In addition, a simple programming language was flashed on the motor so that different sensorimotor loops can be tried out. Using a simple robotic body, interactions of the robot with the environment, but also with the students, were explored, so that a deep understanding of the content emerges.

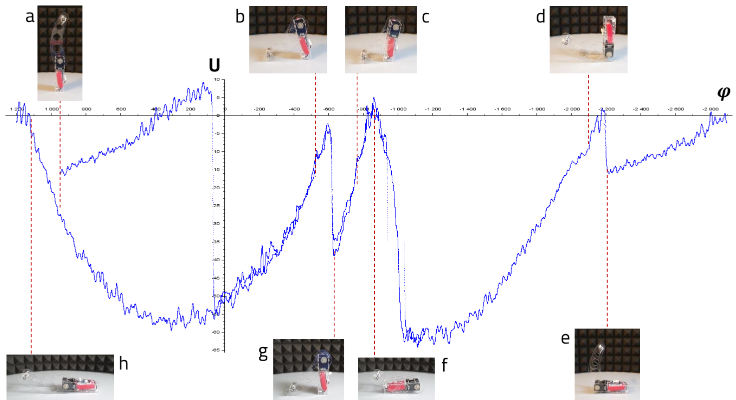

Fig. 5. Recording of joint angle and motor voltage in one experiment (see text). Horizontal axis is the joint angle φ where 360° are divided into 2^{12} steps. The vertical axis represents the motor voltage U where -60 is 0.7 volt.

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