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Inverse biomimetics: How robots can help to verify concepts concerning sensorimotor control of human arm and leg movements

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ABSTRACT

Simulation test, hardware test and behavioral comparison test are proposed to experimentally verify whether a technical control concept for limb movements is logically precise, physically sound, and biologically relevant. Thereby, robot test-beds may play an integral part by mimicking functional limb movements. The procedure is exemplarily demonstrated for human aiming movements with the forearm: when comparing competitive control concepts, these movements are described best by a spring-like operating muscular-skeletal device which is assisted by feedforward control through an inverse internal model of the limb – without regress to a forward model of the limb. In a perspective on hopping, the concept of exploitive control is addressed, and its comparison to concepts derived from classical control theory advised.

1. Introduction

In biomimetics, often also called bionics, problem solutions which have been developed by nature are transferred into engineering. Inverse biomimetics means that accumulated knowledge of engineers about how to build and operate machines is applied to explain biological phenomenons. The machines considered in this paper are robots. The word *robot* was first used in 1921 by the Czech writer Karel Čapek in his play *RUR (Rossum's Universal Robots*). The play concerns factory-made artificial people called *robots* invented to disburden men from heavy and dangerous work. At the end, however, the robots extinguished the mankind. According to the Robotic Institute of America (1979), the word *robot* describes "a re-programmable, multifunctional manipulator designed to move material, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks". In contrast to this rather industrial meaning, we also speak about "humanoid robots" in the sense of Isaac Asimov's famous collection of stories titled "I, Robot" published 1950, if those machines have a more or less human-like body, move like humans, communicate with humans via gestures or speech, act as artists, or behave as intelligent autonomous agents. Obviously, such robots are built to mimic and/or accomplish sorts of human- or animal-like behavior, and to demonstrate the actual state of mechanical and/or electrical engineering.

Here we suggest to use robots in the reverse direction, namely to substantiate hypotheses or theories about the generation of human or animal behavior. Literature in the behavioral sciences provides countless models invented to describe and explain the emergence, development and evolution of behavior. The challenge, however, is the experimental verification that a presumed modality of behavioral control could be indeed realized in the biological system under consideration. The present paper deals with this verification: it describes a test procedure by which we can get information about the type of movement control employed by an organism in a given scenario, exemplifies the procedure for aiming movements, and gives a preview on corresponding efforts concerning hopping behavior. In this procedure robotic test-beds play a significant role.

1.1. Formal verification procedure

The verification procedure demands to consider an organism under cybernetic aspects, that is to say, to split it into body and limbs regarded as parts of the physical environment, and a controller embodied elsewhere, for instance in the nervous system. According to control theory (for technical details see for instance Sciavicco and Siciliano, 2005), in limb movements the controller is conceived a functional unit that gets the measured kinematics (position, velocity and acceleration) of the limb to be controlled, and its desired kinematics. From both variables the controller com-

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putes those forces which, when applied to the limb, make the difference between the actual and desired trajectories as small as possible, whereby the limbs are considered as underlying rigid body mechanics. In the present paper we understand control in a broader sense as an algorithm supposed to make the limb move in the observed manner.

To verify – or to reject – a concept composed of the physically described limb and the suggested type of control, we follow a procedure which consists of three steps: the simulation test, the hardware test and the behavioral comparison test.

The simulation test has to be conducted at first. It checks whether the limb model and the control model can be cast into an executable computer program. The test will uncover logical and conceptional faults of the control model, the limb model, and the interconnection of both. Notice, however, that it is practically impossible to simulate a biological system in its full – or almost full – complexity. Complexity should rather be confined to the minimal level necessary to guaranty the functional equivalence between the simulated and the real movement under consideration, and between the simulated and real ambient conditions (scenario) under which the movement is executed. Even most sophisticated relationships inserted into the simulation code can reveal in the behavioral comparison test as indistinguishable from simpler codes.

The hardware test should only be arranged, if the simulation test succeeded. A machine has then to be built which functionally replicates the simulated limb model. Because these machines are scientific tools to investigate human motor behavior, they usually mirror functions of legs, arms and hands. Such machines are commonly called robots. A robot when employed as a test-bed for control concepts proofs whether real world conditions have been overlooked in the simulation, for instance bad structural components, constraints imposed by the materials used, or randomly and seldom occurring events. The hardware test thus helps to avoid misinterpretations of results due to an incongruence between the simulated and the real world. The hardware, therefore, can only be replaced by software, if the functional conformity between the simulated and the real environment has been carefully proved true previously, as it is – or should be -the case, for instance regarding the industrial standard "hardware in the loop" (HIL). As a matter of fact, the hardware test of the verification procedure is often the most costly part, in terms of labor, time, as well as of money, but is often also mostly underestimated, unrecognized and misconceived by the addressee. Keep, however, in mind, that a machine can never resemble its biological counterpart in each detail. Necessary is only the functional equivalence of both with respect to the movement under consideration, and of the scenario under which the movement is executed in the simulation and in the real world. So, simply designed robots often suffice.

The behavioral comparison test is the last step of the procedure. Here, experimental human or animal data are confronted with data from simulations yielded under the same scenario as in the experiment. Notice that this test compares human data not directly with robot data, but with simulated data, however, produced by aggregates which passed a rigorous reality check. This frees from the requirement to repeatedly alter the hardware if the robot marginally deviates from humans. It is essential to also include external (non-systematic) limb perturbations in this scenario, because the controller has to deal with systematic (that are predictable) and unsystematic (that are unforeseen) effects as well. Often only such perturbations can differences between systems and approaches make manifest. The actual task of the behavioral comparison test is the provision of a quantitative measure of the conformity between the experimental human data and the data originating from the control concept applied to the simulated limb. Because human data in general exhibit a natural random variability, the behavioral comparison test shall include a statistical check whether the conformity measurements exceed this random variability significantly. So, different control concepts become comparable with respect to a statistical criterion, and it is even thinkable that different control concepts reveal as statistically indiscernible with respect to human (or animal) data.

The test trilogy outlined above, therefore, provides a strategy to check the probability, by which a technical concept concerning the control of behavior – here of limb movements -applies also to humans. It further frees from the trend to develop robots and control models of escalating complexity, and a detailedness far from being specifiable through the behavioral comparison test.

1.2. Verification and Experiment

The test trilogy ensues from the need to apply the scientific method to a chosen subject. The subject here is sensorimotor control in humans and animals. The approach firstly requires to specify a scientific hypothesis, here to specify a technically practicable control concept supposed to generate the observed movement. Then one has to derive questions from it, and to mold each question into an experimental design, where an isolated independent variable is manipulated, and the effect on the dependent variable is observed. If proceeding in this manner, a positive result can be interpreted as a causal relationship between both variables, which is combinable with the findings of other experiments, whereas a non-positive result may justify to refute the underlying assumption. Simulation test and hardware test serve to assure the scientificity of the hypothesis, whereas the behavioral comparison test refers to the experimental part. As a rule, the method demands a rigorous and artful simplification and a "break down" of the biological system into isolated functional units, since otherwise experiments are hardly to conduct. This is at the expense of the full real life diversity, but to the advantage of getting explanations of single and previously mysterious events. At long sight, knowledge about the world thus becomes step by step available. The pieces can be re-assembled in different ways to get deeper insights into a multitude of natural phenomena, or to build machines never seen before and specifically tailored to a specific topic of research.

1.3. Application of the verification procedure

In the following second chapter, the complete test trilogy as sketched above is exemplarily applied to goal-directed forearm movements. In the third chapter we give a perspective on hopping behavior. The related investigations, too, are planned to follow the test trilogy scheme, but are yet fragmentary.

2. Control of goal-directed forearm movements

In aiming, the respective limb freely moves from a start position to a desired position where the limb stops and/or comes into interaction with surrounding parts of the physical environment. The question is, what type of control does generate the observed human movement trajectories? The study which is reported here was motivated by the existence of several competing control models for aiming movements. The models which can be paraphrased as (a) muscular servo hypothesis, (b) peripheral sensing hypothesis, (c) equilibrium hypothesis and (d) revised spring model, are in our opinion the most important ones.

2.1. Outlines of the concepts to be tested

The following explanations are rigorously restricted to forearm movements about the elbow joint with the upper arm fixed, and concern the physiological concepts the four models are based