

A bio-inspired architecture for movement generation based on discrete and rhythmic movement primitives modeled by dynamical systems

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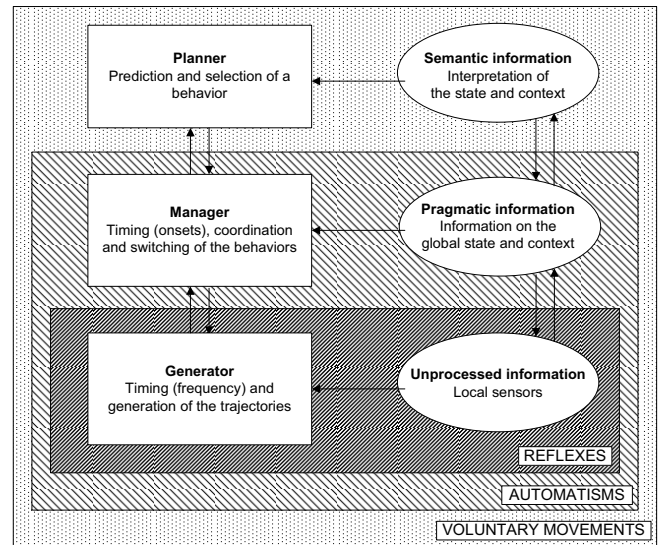
In the framework of the European project RobotCub (www.robotcub.org), which aims at developing a baby-like robot with the motor and cognitive abilities of a 1.5 years old child, our purpose is to design a functional model of the human motor system. Indeed, applying a model of the human motor system to robots is interesting for at least two reasons. Firstly, for testing hypotheses on movement generation: neuroscience theories relative to movement generation can be corroborated or discarded by testing them on robots. Secondly, for bringing new ideas to control robots: human are capable of dealing with high redundancies and of generating complex movements in a very efficient way that no robot can challenge yet.

Movement generation in humans appears to be processed through a three-layered architecture, where each layer correspond to a different level of abstraction in the representation of the movement. In our model, those levels are functionally defined as the planner, the manager and the generator.

The planner (i.e the motor cortex in humans) builds the mental representation of the task. Indeed, in order to choose to perform a given action, we must be able to predict its consequence on the environment and on ourselves and an internal model of the environment and the self is thus needed. The manager (the brain stem, the basal ganglia and the cerebellum in humans) is involved in the selection, timing and coordination of the appropriate behaviors (motor programs). Finally, the generator (the spinal cord) generates trajectories through central pattern generators, i.e. networks of neurons involved in the production of rhythmic and discrete movement primitives.

Each of these levels influence each other and are working in parallel during movement generation. Such a three-layered architecture allows for an easy definition of the three types of movements distinguished in animal motor control, namely (i) reflexes, i.e. genetically inherited responses to stimuli; (ii) automatisms, i.e. learned responses to given stimuli and (iii) voluntary movements, i.e. movements based on a mental representation of the task (that we call an internal model accordingly to [1]). Those three movements clearly correspond to different cognitive levels; we strongly think that they co-evolve and are built upon each other. The architecture we use, depicted on the figure below, seems thus to be a suitable

platform to consider human movements in a broad sense.



The whole structure is fed back by sensory information which is distributed along the motor structure in the same three-layered fashion, accordingly to its degree of processing, namely (i) unprocessed information (cutaneous information, state of the muscles, load, ...), that is required for fast, protective movements (reflexes), (ii) pragmatic information (global states of the system, position of objects, ...), that triggers learned responses to the specific context (automatisms) and finally at the higher level, (iii) semantic information (signification of the environment, state of mind, ...), that contributes to the mental representation of the context involved in voluntary movements.

Moreover, we make the assumption that movements are generated in a modular way, both in terms of pattern generator (movement primitives) and of motor programs (predefined set of trajectories, i.e combinations of movement primitives) found in biology ([2],[3],[4]). Such an assumption turns a high dimensional trajectory generation into a simple selection between predefined behaviors; it is thus well suited for fast adaptive behaviors.

We focus in particular on the distinction between discrete (aperiodic and finite) and rhythmic (periodic) movements. Schaal et al. ([5]) have shown that rhythmic movements are not a particular case of discrete movements by using fmri techniques; some brain areas in-

volved in discrete task are not active during rhythmic movements. Such a distinction is convenient for modeling purposes. Our trajectories are generated using a network of coupled dynamical systems, accordingly to the biological concept of central pattern generators (see [6] for a review); we use the system that we have previously developed which allows the generation of discrete (i.e. short-term) and rhythmic movements and the combination of both (i.e. oscillations around time-varying offsets). Such an approach allow us to use the stability properties of dynamical systems to ensure a robust control of the movements.

However, if mathematically defining rhythmic and discrete movements is an easy task (rhythmic refers to periodic signals, discrete to aperiodic ones), when considering movements that we actually perform, the task starts being tricky (see [7] for instance), the major problem being that movements are finite in time and that the formal, mathematical definition of periodicity is thus unusable. Moreover inner variability of movements and modulations by the environment (contacts for instance) change the basic nature of the performed trajectory.

A review of the literature leads to the observation that rhythmic and discrete movements have mainly been studied separately, although some interesting articles on their combinations exist (see [8] for a review). This distinction is mainly due, from our point view, to two interlinked factors. Firstly, rhythmic and discrete movements are perceived as representatives of two different levels of movement generation, i.e. automatic and voluntary levels. Indeed, locomotion is a typical example of a rhythmic behavior that can be found in species with very low cognitive abilities, whereas a behavior as reaching can only be observed in more evolved ones. This implies different investigation techniques; most of the studies on rhythmic movements have been made on (de)cerebrates) vertebrates and invertebrates, whereas discrete movement is usually studied using kinematic data or brain imaging recordings of humans or primates. Note that force fields ([3],[9]), i.e. spinal generators of discrete movements, is an important exception to this. Secondly, rhythmic and discrete movements have not been studied per se in general, but mainly as outcomes of some specific processes in the trajectory generation, namely the generation of periodic outputs by the central pattern generators (CPGs) at the spinal level for rhythmic movements and movements involving high level planning for discrete movements.

We propose to address discrete and rhythmic movements from a hierarchical point of view, i.e relatively to the three entities we defined above. Our analysis leads us to propose a functional distinction based for instance on the relationship of the movements with time. Indeed in rhythmic movements the general duration of the movement has no influence on the timing between the mus-

cles activation, whereas in discrete movement the general duration of the movement modifies this relative timing. Accordingly, recent studies have postulated that different timing processes could be involved depending on the features of the task to be performed. Named automatic or cognitively controlled timing ([10]), or emergent and explicit timing ([11]), the two processes are involved in the timing of respectively periodic, highly predictable movements at the spinal level and of discontinuous and unpredictable ones at the cerebral one.

We will discuss such a functional approach to rhythmic and discrete movements and propose a control architecture to account for them. Results obtained in simulation using the baby robot iCub will be then presented, notably on switching between discrete and rhythmic movements (namely reaching and crawling) and superimposing both behaviors (reaching while crawling).

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