Discrete-Event Systems for Modelling Decision-Making in Human Motor Control

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Abstract. Artificial intelligence, control theory and neuroscience have a long history of interplay. An example is human motor control: optimal feedback control describes low-level motor functions and reinforcement learning explains high-level decision-making, but where the two meet is not as well understood. Here I formulate the human motor decision-making problem, describe how discrete-event systems could model it and lay out future research paths to fill in this gap in the literature.

Keywords: Online control · Decision-making · Limited lookahead · Reinforcement learning · Human motor control

1 Introduction

The role of decision-making in human motor control can be considered using artificial intelligence, control theory and computational neuroscience. Although optimal feedback control (OFC) describes low-level human motor control and reinforcement learning (RL) can explain high level decision-making, there is a gap in our understanding when motor control meets decision-making.

Decision-making is a discrete process: a possible option is taken or not. This naturally suggests discrete-event systems (DES) as a paradigm. DES for hierarchical, online and optimal control are of particular interest because these capture specific aspects of human motor decision-making.

My hypothesis is that "decision-making in human motor control for reaching-based tasks can be modelled using online control for dynamic DES." In the remainder of this paper I formulate the human motor decision-making problem, summarize three approaches to DES control and identify lines of inquiry.

2 Problem Definition

Scott's taxonomy of sensory feedback processing for motor actions leads to a hierarchical view of the human motor system (Fig. 1) [6]. The continuous motor

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commands to a goal are captured by OFC, [7], but how that goal is selected is less understood. Put another way, although the control of a reach is understood, the selection of its target is less clear.

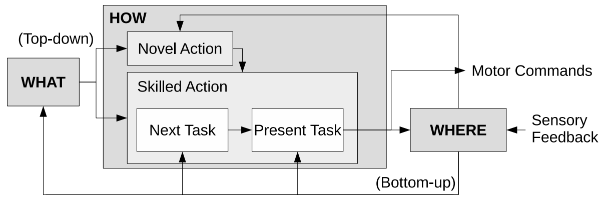

Fig. 1. Functional divisions of the human motor control system, adapted from Scott [6]. Defining a motor action's goal and defining the subsequent motor action's goal take place in the "Present Task" and "Next Task" blocks respectively.

The link between motor control and decision-making has been shown using statistical decision theory to explain movement under different conditions [9]. Although skilled motor control results from a series of decisions and although both have been well-studied individually, Gallivan et al. highlight that a gap exists in the literature for decision-making and motor control together [3].

3 Discrete-Event System Models for Decision-Making

DES models processes as automata and their behaviour as formal languages containing actions that are either controllable or uncontrollable and observable or unobservable. A supervisor enacts control by constraining the process's language to a set of desirable behaviours [10, Ch. 3], resulting in computationally tractable models and provably correct supervisors.

3.1 Hierarchical control

Control problems can be decomposed into hierarchies when functional divisions in its task lead to top-down/bottom-up processes, e.g. human motor control [6]. Hierarchical control for DES results in models with multiple layers. Each layer has a different view of the environment with higher layers exhibiting broader temporal horizons or deeper logical dependencies than lower layers [10, Sec. 5.1].

Specific questions to investigate for hierarchical control are, "how many layers are needed to capture human motor decision-making?" and "what is the minimum information required by each level to effect motor control?"

3.2 Online and optimal control

Another important part of the human motor decision-making problem is the dynamic environment. Not only is the OFC policy being executed in real-time, but so is sensory integration, optimal state estimation and goal estimation [6].

The DES literature includes approaches for large state-spaces, complex possible behaviours and time-varying components where supervisor synthesis is impractical. In these cases an online DES controller is synthesized instead to implement a limited lookahead policy (LLP) that will guide decision-making [1].

Online controllers such as these can also be used to optimize some utility or cost function. Grigorov and Rudie demonstrated that the size of the lookahead window used by a model greatly impacts the utility of its decisions and, critically, that larger windows are not necessarily better [4]. This work provides a concrete framework for combining the online nature of human motor decision-making and the utility inherent in the different options considered.

Specific questions to address include "how are sensory feedback and the efference copy incorporated into the decision-making process?" and "what environmental variables impact the size of lookahead window used by humans?"

3.3 Learning the model

Although the primary goal of this research is a DES model of human motor decision-making for reaching-based tasks, there is a deeper question that must be asked as well. For any model that we propose, can the human brain learn it?

RL captures how past experiences can be used to shape future outcomes; its role in human decision-making as well as a possible neural basis have both been subjects of investigation [5]. In the field of DES, RL has been used to synthesize supervisors for optimal control in online environments [8].

4 Experimental Design

Thought has also been given to experimental designs for which DES models of human behaviour could make testable predictions. Diamond et al.'s recent work used a reaching-based foraging task to isolate the decision-making/motor control link (Fig. 2) [2]. This task is an attractive starting point because it restricts the range of movement to reaching, provides easy-to-interpret discrete goals, and permits a wide range of possible variations.

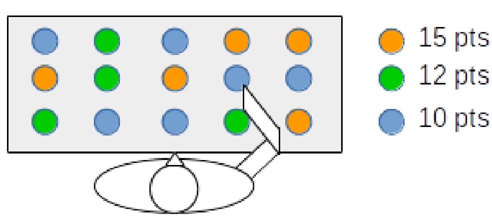

Fig. 2. Diamond et al.'s foraging task, figure adapted [2]. Targets are assigned a value based on size or colour; participants are then instructed to maximize the value harvested within a limited amount of time [2].

Analysis will be required to determine which values for the independent variables will be the most illustrative; one possible path is to run simulations with the developed DES models to pinpoint potential critical points for decision-making.

5 Conclusion

The human motor decision-making problem represents a fusion of motor control and decision-making and its solution will require contributions from multiple fields. This paper formalized the problem of interest and identified goal definition for present and upcoming actions as excellent candidates for modelling by DES.

This paper also summarized concepts from DES control that fit naturally with the human motor decision-making problem: hierarchical, online and optimal control. Each of these suggests specific research questions to ask about the larger problem and whose answers would contribute to the literature.

In parallel to this problem, the question of how any model could be (continually) learned was also identified, leading to the idea of incorporating RL into a holistic framework for human motor decision-making.

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