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An optimal control strategy for hybrid actuator systems: Application to an artificial muscle with electric motor assist

Koji Ishihara *, Jun Morimoto

Department of Brain Robot Interface, ATR Computational Neuroscience Laboratories, Kyoto, 619-0288, Japan
Graduate School of Information Science, Nara Institute of Science and Technology, Nara, 630-0192, Japan

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ABSTRACT

Humans use multiple muscles to generate such joint movements as an elbow motion. With multiple lightweight and compliant actuators, joint movements can also be efficiently generated. Similarly, robots can use multiple actuators to efficiently generate a one degree of freedom movement. For this movement, the desired joint torque must be properly distributed to each actuator. One approach to cope with this torque distribution problem is an optimal control method. However, solving the optimal control problem at each control time step has not been deemed a practical approach due to its large computational burden. In this paper, we propose a computationally efficient method to derive an optimal control strategy for a hybrid actuation system composed of multiple actuators, where each actuator has different dynamical properties. We investigated a singularly perturbed system of the hybrid actuator model that subdivided the original large-scale control problem into smaller subproblems so that the optimal control outputs for each actuator can be derived at each control time step and applied our proposed method to our pneumatic–electric hybrid actuator system. Our method derived a torque distribution strategy for the hybrid actuator by dealing with the difficulty of solving real-time optimal control problems.

1. Introduction

Although robotics technologies have rapidly improved and are widely used in industry and daily life, it remains difficult for robots to generate human-like flexible movements to work in cluttered environments (Defense Advanced Research Projects Agency, 2015) or to assist human behaviors (Ansari, Atkeson, Choset, & Travers, 2015). One reason that deters the development of such robot systems is that robots lack a light, compliant but strong actuator that works like the human muscles. As a matter of practice, electric motors with high reduction gears, which are dominantly used as robot actuators, tend to be heavy and rigid for generating large torques. Although such muscle-like actuators as a pneumatic artificial muscle (PAM) have similar properties to human muscles, control latency due to the air flow is inevitable since PAM uses air pressure to generate joint torque. Therefore, PAM has not been widely used in robot systems.

On the other hand, humans use multiple muscles to efficiently generate a joint movement. For example, at least the biceps and triceps are involved in the one degree of freedom of an elbow joint movement. In the biceps, there are two different bundles: biceps long head and biceps short head. The triceps has three different bundles: triceps long head, triceps lateral head, and triceps medial head (Burdet, Franklin, & Milner, 2013). Similarly, from a technical point of view, robots might be able to use multiple actuators to generate a joint motion. To explore this possibility, hybrid actuation systems have been developed and implemented in robot systems (Hyon, Morimoto, Matsubara, Noda, & Kawato, 2011; Noda, Teramae, Ugurlu, & Morimoto, 2014; Sardellitti, Park, Shin, & Khatib, 2007). However, how to distribute the desired torque to each actuator has not been scrutinized. One possible approach to cope with this torque distribution problem is using an optimal control method (Matsubara, Noda, Hyon, & Morimoto, 2011; Teramae, Noda, & Morimoto, 2014). The optimal control framework provides a powerful tool for robot motion generation in a diverse set of tasks and applications to actuator control (Braun, Howard, & Vijayakumar, 2012; Haddadin, Weis, Wolf, & Albu-Schäffer, 2011) since optimal motor commands can be derived under the constraint of their own dynamics by specifying simple high-level task goals. However, solving an optimal control problem at each control time step has not been considered as a practical approach due to the large computational burden.

In this paper, we propose a computationally efficient method to derive an optimal control strategy for a hybrid actuation system composed of multiple actuators, where each actuator has different

* Correspondence to: Department of Brain Robot Interface, ATR Computational Neuroscience Laboratories, 2-2-2, Hikaridai Seika-cho Soraku-gun, Kyoto, 619-0288, Japan.

E-mail addresses: ishihara-k@atr.jp (K. Ishihara), xmorimo@atr.jp (J. Morimoto).

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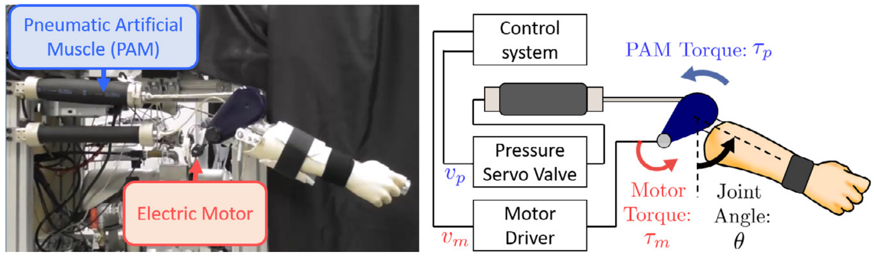

Fig. 1. Forearm robot with pneumatic–electric hybrid actuator system: pneumatic artificial muscle dominantly generates torques but is assisted by small and lightweight electric motor for precise movements. v_p denotes voltage input for air valve, and v_m denotes voltage input for motor driver. We used one pneumatic artificial muscle and one electric motor.

dynamical properties. We derive a new singularly perturbed system of hybrid actuator dynamics to subdivide the original control problem into smaller subproblems so that the optimal control outputs for each actuator can be derived at each control time step. The singularly perturbed system has been intensively studied to describe fluid dynamics (Lagerstrom & Casten, 1972; Van Dyke, 1975), which shows different properties in the regions close and far from the wall due to its viscosity. Inspired by these kinds of studies, it was found that even robot systems, which have particular dynamic properties such as a biped robot or a flexible robot manipulator, can be represented as singularly perturbed systems (Arimoto & Miyazaki, 1980; Siciliano & Book, 1988).

A method that derives optimal control outputs at each control time step is known as Model Predictive Control (MPC). MPC methods have been applied to such slow dynamical systems as chemical plants (Qin & Badgwell, 1997) or ship maneuvering problems (Seguchi & Ohtsuka, 2003) since a sufficient amount of time for calculating the computationally intensive optimal control problem can be used in slowly responding systems. However, directly applying MPC to the real-time control of such faster dynamics as robot systems is unrealistic. In this study, we newly derived singular perturbed system for a hybrid actuator and applied MPC to the subdivided control problems. Based on an idea of using MPC for a simulated system that includes different time scale dynamics (Chen, Heidarinejad, Liu, & Christofides, 2012; Ishihara & Morimoto, 2015), we developed a two-stage MPC framework for the hybrid actuation system and showed that our proposed method was able to successfully control the real robot. Both optimization stages correspond to either the extracted fast components of the singularly perturbed system or the original dynamics that include a slow dynamical component. Then for the fast dynamical component, we propose short-term optimization with fine-control time resolution. Since a robot can quickly change its behavior with the fast dynamical component, the long-term optimization is not necessary. Instead, we can utilize computational resources to generate precise movements with higher time resolution. On the other hand, for the original dynamics, we address long-term optimization with coarse-time resolution. Since a robot cannot quickly change its behavior with the original dynamics that includes the slow dynamical component, we need to consider the long-term optimization problem. However, for the original dynamics, we can use the optimization problem with lower time resolution that requires less computation since we can rely on the optimization of the fast dynamical component to generate movements for fine-time resolution.

To evaluate the torque distribution performance of our proposed approach, we applied the two-stage optimization procedure to our pneumatic–electric hybrid actuator system, where PAM dominantly generates joint torques but is assisted by a small and lightweight electric motor for precise movements (Fig. 1). We first derived a singularly perturbed system for the hybrid actuation system based on the difference of the dynamic properties between

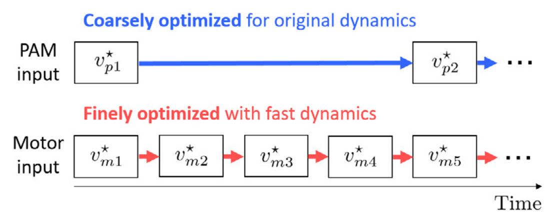

Fig. 2. Two-stage optimization strategy: Each thread corresponds to either fast component of singularly perturbed system or original system. For fast dynamical component, we propose short-term optimization with fine-control time resolution. Since a robot can quickly change its behavior with fast dynamical component, long-term optimization problem is not necessary and we utilize computational resources to generate precise movements with higher time resolution. For original dynamics, we address long-term optimization with coarse-time resolution. Since a robot cannot quickly change its behavior with original dynamics that includes slow dynamical component, we need to consider long-term optimization problem. However, in two-stage optimization strategy, we can use optimization problem with lower time resolution that requires less computation since we can rely on optimization of fast dynamical component to generate movements for fine-time resolution. v_p denotes voltage input for air valve, and v_m denotes voltage input for motor driver.

PAM and the electric motor. From this theoretical analysis, we found that only the lower-dimensional subspace of the original system needs to be considered in the fast dynamical component and that only the electric motor outputs affect the behavior of the lower-dimensional subspace. Our method properly derived a torque distribution strategy for the hybrid actuation system by solving a real-time optimal control problem and successfully reduced the computation time without significantly deteriorating the control performance. In the proposed approach, after deriving the optimal input voltages for the air valve and the motor driver with coarse-time resolution, only the optimal sequence of the input voltage for the motor driver was further optimized with fine-time resolution under the lower-dimensional dynamics (see Fig. 2). For a comparison, we also applied two standard implementations of the MPC method with two different time resolutions each: optimal control strategies with fine-time resolution and coarse-time resolution to our hybrid actuator system. The coarse strategy corresponds to the optimization process for the original dynamics of our proposed method. Therefore, we can evaluate the effectiveness of the optimization for the fast dynamics component by comparing the tracking results of the coarse strategy and our proposed approaches. To the best of our knowledge, for the first time in the literature, a real robot with a hybrid actuator system is proposed as a singularly perturbed system and is successfully controlled in real-time with the new two-stage optimal control method.

The rest of our paper is organized as follows. Section 2 explains a standard MPC problem. Section 3 introduces our proposed two-stage optimal control method. Section 4 describes about the tasks, their goals and experimental setting. Section 5 shows the experimental results .