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Distributed control of multi-agent systems over unknown communication networks using extremum seeking

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ABSTRACT

In this paper, the solution of large-scale real-time optimization problems of multi-agent systems (MAS) is tackled in a distributed and a cooperative manner without the requirement of exact knowledge of network connectivity. Each agent in the communication network measures a local disagreement cost in addition to its local cost. The agents must work collaboratively to ensure that the system's unknown overall cost (i.e., the sum of the local cost of all the agents) is minimized. In order to minimize this cost, the local disagreement cost of all the agents must first be minimized. This minimization requires the solution of a consensus estimation problem and ensures that the agents reach agreement on their decision variables. To address this challenging problem, a distributed proportional-integral extremum seeking control technique is proposed, one that solves both problems simultaneously. Three simulation examples are included, they demonstrate the effectiveness and robustness of the proposed technique.

1. Introduction

Several control techniques have been proposed and employed in solving real-time optimization problems, they range from model based to model free. When the situation entails addressing large-scale real-time optimization problems involving multi-agents, these techniques are basically grouped as either centralized or distributed (decentralized). In a centralized environment, a single decision maker controls the actions of all agents in the system. This decision maker monitors, receives and processes information from and sends processed results back to the agents. This means that the decision maker has complete knowledge of the state of the system at all times and can make useful decision(s) that help meet global objective(s). One draw back of this approach is the increase in computational complexity that arises as the number of agents increases. This could result in the transmission of inaccurate information, loss of information and increase in computation time. In addition, centralized approaches are complex, expensive and problem specific. Furthermore, centralized approaches lack system robustness as they are inefficient in a dynamic environment and the failure of the decision maker could mean failure of the entire system.

Most of the challenges highlighted above are absent in a distributed environment. This is because a distributed approach involves multiple decision makers that are able to make individual decisions. Each decision maker controls an agent and limits the agent's task to the solution of a simpler local problem. Each local problem can be tackled in a cooperative (through local communication with neighbouring agents) or an uncooperative fashion. Some of the advantages of distributed control over centralized control include but are not limited to effectiveness, flexibility, scalability and adaptiveness. The greatest advantage of distributed control is system robustness. This implies that the failure of a decision maker does not necessarily mean overall system failure as the system can absorb the effect of a failure and quickly recover through the help of other decision makers.

In light of the advantages of distributed control, extensive research is being carried out in addressing control and optimization problems of MAS in a cooperative and an uncooperative manner. Researchers are focused on the development and analysis of new distributed techniques for the solution of such problems which are obviously difficult or impossible to solve using centralized approaches. Solving distributed control problems may require the agents in the network to reach agreement on some quantity of interest. This means solving a consensus estimation problem and such problems can be tackled using a consensus estimator. Several consensus algorithms have been proposed in the literature, see [1–6]. Distributed techniques have been proposed to tackle resource allocation problems. In a distributed but an uncoopera-

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tive fashion, the problem of finding the optimal resource allocation (from a finite set of resources) that maximizes an unknown overall welfare function was considered in [7]. It was demonstrated that the agents can work independently to achieve the desired objective. In [8], a distributed subgradient technique was proposed for use in a cooperative manner to address resource allocation problems involving welfare functions that are known, convex and nonsmooth. The technique can be employed to address consensus estimation problems. The combination of extremum seeking control with a local replicator system was employed in the design of a distributed technique that solves resource allocation problems of MAS with stable dynamics [9].

Stochastic extremum seeking control was employed in an attempt to address a source seeking problem of MAS in an uncooperative manner [10]. The deployment of a group of vehicles (agents) in a planar signal field was considered. Each agent had access to the measurement of an unknown nonlinear cost that represented the spatial distribution of the signal. The unknown cost had a local minimum that was desirable. The technique used considered random perturbations as the excitation signal in the extremum seeking scheme and also required the agent to work in a leader–follower fashion. In solving formation control problems (where the goal is to find the maximum separation distance among agents in order to maximize a cost), it is known that changes in the environment can affect communication quality and the control of agents, hence the use of adaptive control techniques such as extremum seeking control. Problems of this form have been tackled in real-time as presented in [11,12] in a cooperative fashion using extremum seeking control. The use of a dynamic average consensus estimator and a proportional integral extremum seeking control technique for solving problems of MAS has been studied. In [13], the distributed optimization for agents with unknown dynamics was presented while problems of stabilization and optimization were addressed simultaneously in [14]. Power maximization problems of wind farms have also been considered and solved cooperatively in [15,6]. To overcome the need to provide accurate models of aerodynamic wake interactions among wind turbines, safe experimentation dynamics (SED) distributed algorithm and the payoff-based distributed learning for Pareto optimality (PDLPO) were proposed in [15] for maximizing farm wide power capture. The perturbation based extremum seeking control technique was employed in [6].

At this juncture, it is evident that extremum seeking control is effective in solving large-scale optimization problems in real-time. It is a well known model-free real-time optimization and adaptive control technique that implements a gradient descent approach requiring only measurements of the output to be optimized. Extremum Seeking Control was first introduced in [16]. As early as 1943, many reports documented investigations in this area [17]. The application of ESC to the optimization of internal combustion engines was first reported in [18], where ESC was referred to as extremum control and self-optimizing control. At this time, there were no concrete analytical or even systematic schemes for ESC. As a result, it became less appealing as other optimization techniques and adaptive control methods became advantageous. In the early 2000, ESC made a strong come back after stability results based on averaging analysis and singular perturbation (standard perturbation based extremum seeking control approach) for a class of general nonlinear dynamic systems was provided [19]. This contribution ignited significant research effort to address the numerous challenges or limitations associated with ESC [20–25]. Alternative ESC techniques with improved performance and robustness have been developed as seen in these literature papers [26–30]. Also, extremum seeking control techniques that eliminate the need for time-scale separation between the system and the optimization dynamics have been proposed in [31,32].

Extremum seeking control has been utilized in solving large-scale optimization problems that employ exact knowledge of network connectivity [13,14,6] but in the absence of such precise knowledge, can large-scale optimization problems of MAS be solved and global objectives met?

The main contribution is the design of a distributed controller that integrates extremum seeking control and proportional-integral consensus algorithm. We demonstrate its utilization in addressing real-time optimization problems over communication networks with uncertain or unknown mathematical descriptions. This control technique can be employed in monitoring processes or plants such as chemical and food plants, water and sewage treatment plants, power and petrochemical plants, pharmaceutical plants, etc. These plants are typically complex networks of smaller interconnected units that are controlled using multiple decentralized controllers. In most integrated environments, these units can exchange local information with neighbouring units over some communication network. With the help of these controllers, their actions can be monitored to achieve some desired process objective. The units may be required to reach consensus or agreement on some specific operating variables. For example, consider a chemical process in which each local controller requires the specific knowledge of a temperature measurement of a feed stream that is only directly available to a few units. If the process is subject to communication limitations, then it is not possible to have this measurement instantaneously reach each unit. In this case, each unit must provide a mechanism to estimate this quantity. The proposed distributed control technique can handle such a task. The algorithm utilizes a parameter estimation routine to estimate key parameters of the cost dynamics. A distributed proportional-integral controller is designed to drive the system to its optimum. The proportional-integral mechanism of the distributed extremum seeking control technique provides two distinct and crucial mechanisms to achieve the real-time optimization objective. The effect of the integral action guarantees that a consensus on the decision variables of the agents is achieved. The proportional action ensures that process-wide optimization objectives are met. A cooperative approach that allows for local communication between the agents is utilized to ensure that global objectives are met. Proof of local convergence of the algorithm to a small neighbourhood of the unknown optimum is included.

This paper is organized as follows. The problem description is stated in Section 2. Section 3 describes the distributed PIESC algorithm. Simulation examples are given in Section 4 and concluding remarks made in Section 5.

2. Problem description

The objective of this study is to develop a distributed extremum seeking control technique to solve real-time optimization problems over an unknown or uncertain communication network in a distributed manner. The idea is to solve an overall optimization problem using only the local action of agents operating over the network. Each agent has only its decision variable (its input), its local cost and local disagreement cost measurements. An agent's input can also be seen as its own estimate of the input of the overall network. Using the communication network, the agents can exchange their local information with their neighbours to achieve a consensus on their inputs. The consensus value reached by the agents is what the overall cost depends upon. Using the proposed distributed PIESC technique, this consensus value is driven to the optimizer of the overall cost. This type of problem can arise in the development of distributed control such as model predictive control in which each local agent requires an estimate of the control moves of the network to solve its own local optimization problem. In this section,

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