

Primal-dual optimization methods for large-scale and distributed data analytics

Došan Jakovetić, Dragana Bajović, João Xavier, José M. F. Moura

Abstract—The augmented Lagrangian method (ALM) is a classical optimization tool that solves a given “difficult” (constrained) problem via finding solutions of a sequence of “easier” (often unconstrained) sub-problems with respect to the original (primal) variable, wherein constraints satisfaction is controlled via the so-called dual variables. ALM is highly flexible with respect to how primal sub-problems can be solved, giving rise to a plethora of different primal-dual methods. The powerful ALM mechanism has recently proved to be very successful in various large scale and distributed applications. In addition, several significant advances have appeared, primarily on precise complexity results with respect to computational and communication costs in the presence of inexact updates and design and analysis of novel optimal methods for distributed consensus optimization. We provide a tutorial-style introduction to ALM and its analysis via control-theoretic tools, survey recent results, and provide novel insights in the context of two emerging applications: federated learning and distributed energy trading.

Index Terms—Augmented Lagrangian; primal-dual methods; distributed optimization; consensus optimization; iteration complexity; federated learning; distributed energy trading.

I. INTRODUCTION

Primal-dual optimization methods have a long history, e.g., [1], [2], [3], [4]. Seminal works include, e.g., the Arrow-Hurwitz-Uzawa primal-dual dynamics [4], and the proposal of augmented Lagrangians and multiplier methods, e.g., [2], [3]; see also [5].

The augmented Lagrangian (multiplier) method (ALM) is a general-purpose iterative solver for *constrained* optimization problems. The underlying mechanism translates the task of solving the original “difficult” optimization problem with respect to the (primal) variable x into solving a sequence of “easier” problems (often unconstrained ones) with respect to x , wherein the influence of the original “hard” constraints is controlled via the so-called dual variables. The ALM mechanism is beneficial in many scenarios; for example, it allows to naturally decompose an original large-scale problem into a set of smaller sub-problems that can then be solved

in parallel. ALM can handle very generic problems, including non-smoothness of the objective function and generic problem constraints and has strong convergence guarantees, e.g., [1], [6], [7], [8], [9].

The past decade shows a strong renewed interest in primal-dual and (augmented) Lagrangian methods. This is because they are, by design, amenable to large-scale and distributed optimization. Indeed, very good performance has been achieved on various Big Data analytics models, including, e.g., sparse regression [10], [11], [12], [13], [14], large-scale model predictive control [15], and low rank tensor recovery [16], and also on various modern real-world applications, such as state estimation for the smart grid, e.g., [17], community detection in social networks, e.g., [18], image filtering, inpainting and demosaicing, e.g., [19], [20], [21], factorization problems in computer vision, e.g., [22], etc.

In this paper, we provide an overview of ALM and related primal-dual methods for large-scale and distributed optimization. We provide a gentle introduction to the topic, followed by an overview of recent results, also suggesting novel insights and potential novel applications. In more detail, we focus on the following key aspects.

- **Approximate updates.** Several recent results consider the scenarios when primal and/or dual variables are updated in an inexact way. The works then study how the inexactness reflects convergence and convergence rate properties of the methods.
- **Distributed optimization.** Primal-dual methods have proved to be very successful in distributed consensus optimization, e.g., [23]. Therein, a set of nodes connected in a generic network collaborate to solve an optimization problem where the overall objective function is a sum of the components known only locally by individual nodes. In this setting, after an appropriate reformulation of the problem of interest, application of primal-dual methods leads to efficient and often to optimal methods. Furthermore, several existing methods that have been derived from different perspectives have been recently shown to admit primal-dual interpretations, which in turn opens up possibilities for further method improvements.
- **Complexity results.** While traditional studies of primal-dual and ALM focus on convergence rate guarantees with respect to the (outer) iteration count, more recent works focus on establishing complexity results with respect to more fine-grained measures of communication and computational costs, such as number of gradient evaluations, number of inner iterations, etc. These results give more insights into the performance of the methods with respect

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