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Dynamic operations and pricing of electric unmanned aerial vehicle systems and power networks

Kaiqing Zhang[a], Liqun Lu[b], Chao Lei[b], Hao Zhu[c], Yanfeng Ouyang[b,*]

[a] Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[b] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[c] Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX 78705, USA

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ABSTRACT

The emergence of electric unmanned aerial vehicle (E-UAV) technologies, albeit somewhat futuristic, is anticipated to pose similar challenges to the system operation as those of electric vehicles (EVs). Notably, the charging of EVs en-route at charging stations has been recognized as a significant type of flexible load for power systems, which often imposes non-negligible impacts on the power system operator's decisions on electricity prices. Meanwhile, the charging cost based on charging time and price is part of the trip cost for the users, which can affect the spatio-temporal assignment of E-UAV traffic to charging stations. This paper aims at investigating joint operations of coupled power and electric aviation transportation systems that are associated with en-route charging of E-UAVs in a centrally controlled and yet dynamic setting, i.e., with time-varying travel demand and power system base load. Dynamic E-UAV charging assignment is used as a tool to smooth the power system load. A joint pricing scheme is proposed and a cost minimization problem is formulated to achieve system optimality for such coupled systems. Numerical experiments are performed to test the proposed pricing scheme and demonstrate the benefits of the framework for joint operations.

1. Introduction

Electric unmanned aerial vehicles (E-UAVs), also called electric drones, are usually referred to as battery-powered, autonomous aircrafts propelled by multiple rotors. In recent years, rapid advances in control technologies and diminishing costs have led to increasing utilization of UAVs, especially E-UAVs, for various civilian purposes, such as aerial surveillance/mapping (Maini and Sujit, 2015; Nintanavongsa et al., 2016; Pugliese et al., 2016; Kaufmann et al., 2018), entertainment (Guerriero et al., 2014), as well as transportation of goods in times of critical need (Kim et al., 2017; Stewart, 2014; Thiels et al., 2015; Ham, 2018). In particular, the booming growth of e-commerce and customers' increasing needs for fast delivery have motivated many leading logistics companies to explore the use of E-UAVs for parcel delivery. For example, Amazon announced its Prime Air in 2013, which is an E-UAV delivery system designed to deliver packages up to five pounds to customers in 30 min or less (Mattise, 2013). German firm DHL launched its Parcelcopter research project in December 2013 (Hern, 2014). More recently, UPS has also unveiled its drone delivery plan, in which E-UAVs can be launched from trucks at selected points along the truck routes (Vanian, 2017).

The aviation industry's interest in E-UAVs has gone beyond aerial surveillance and freight delivery, and has turned toward passenger transportation. Recently, Zunum Aero, a company funded by Boeing and JetBlue, revealed its plan to create a hybrid

* Corresponding author.
E-mail address: yfouyang@illinois.edu (Y. Ouyang).

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electric aircraft that can offer cheap commuter flights by 2020 (Etherington, 2017). The U.S. flying-car startup, Terrafugia, is aiming to have its autonomous flying vehicle, called the TF-X, flying commercially by 2025 (Muoio, 2016). The German startup Volocopter, which launched in 2011 the first helicopter powered solely by electricity, is also developing the fleet of air taxis (Muoio, 2017). Another German startup called Lilium Aviation successfully completed a test flight of its all-electric, vertical take-off and landing (VTOL), two-seater prototype in April 2017 (Hawkins, 2017). As such, while E-UAVs have not been put into commercial use quite yet, we believe that it is only a matter of time for wide applications of E-UAVs to appear in the very near future.

Many challenges that have arisen nowadays for traditional electric vehicles (EVs) can be anticipated for future applications of E-UAVs, mainly due to their similarities in terms of energy source and recharging needs. In particular, even with recent battery recharging technologies, EVs still have relatively limited travel ranges and long charging times. Such limitations have led to numerous studies on planning infrastructure and traffic routing for en-route EVs (Chen et al., 2016; Worley and Klabjan, 2011; Worley et al., 2012). Similarly, even though many efforts have been put into developing E-UAV technologies, the short flight range owing to limited battery capacity still poses a great challenge. Several strategies have been proposed to overcome the range limitations of E-UAVs. Some researchers have put their focuses on designing a multi-modal truck-drone delivery system, where drones are carried to the vicinity of customers by a fleet of trucks so as to cover only “the last mile” (Agatz et al., 2018; Ferrandez et al., 2016; Ha et al., 2015; Luo et al., 2017; Murray and Chu, 2015; Poikonen et al., 2017; Wang et al., 2017), where E-UAVs are launched at stops along the truck routes and return to the trucks after delivery. Alternatively, Sundar and Rathinam (2012, 2014) introduced a so-called fuel-constrained E-UAV routing problem, where an E-UAV is allowed to refuel/recharge at any of refueling depots such that all delivery targets are visited and the total fuel consumption is minimized. Along this direction of inquiry, some researchers examined E-UAV systems supported by automated refueling stations that enable long-term or persistent services (Kim et al., 2013; Kim and Morrison, 2014; Song et al., 2014, 2016; Hong et al., 2018). Dorling et al. (2017) proposed a multi-trip vehicle routing model that allows multi-rotor E-UAVs to make multiple returns to the depot to replace batteries. Most of these studies assumed that the batteries can be replaced instantly or the charging time is negligible. Therefore, no consideration is cast over the impacts of charging activities on not only the E-UAV operations, but also the associated infrastructures (such as charging stations and the underlying power grids).

However, we can foresee that the huge electricity demand from E-UAV charging, in particular for en-route charging from inter-city trips of E-UAVs, would pose a great impact on power grids, just similar to the challenges faced by the EV industry nowadays (Ma et al., 2012; Xu and Pan, 2012). Furthermore, since the travelers’ en-route charging decisions are highly related to their travel behaviors (Sweda and Klabjan, 2012; He et al., 2014; Adler et al., 2016), it is imperative to investigate the interactions and joint operations of the coupled power and transportation systems. Some earlier efforts have been made towards the EV practice; e.g., Alizadeh et al. (2015) proposed a joint charging pricing mechanism that maximizes the welfare of both travelers and power generators, assuming travelers’ travel choices can be controlled via proper roadway tolls. He et al. (2013) considered an equilibrium framework that captures the interactions among the availability of public charging opportunities, the charging prices, and the route choices of EVs. Even though these studies mainly focus on a static setting, they indeed remind us of potential challenges that might occur when E-UAVs become commercialized for both freight and passenger transportation.

In this paper, we consider the operations of a coupled system of aviation transportation and power networks, and address the temporal fluctuation of electricity prices caused by *time-varying* E-UAV travel demand and power base loads. Although it is known that both the power and aviation transportation systems may be ideally operated in a demand-responsive and dynamic way, there is still likely a long way ahead before we achieve that status, because of technical and regulatory barriers. As an initial step toward the foreseeable future, this study focuses on a possible scenario that may occur in the next 5–10 years. Hence, we assume that the anticipated systems still share some similarities with the current ones: (i) For the power system, we assume a day-ahead wholesale electricity market (which is the current industry practice (US Federal Energy Regulatory Commission, 2003)), where the locational marginal prices (LMPs) of electricity (Glover et al., 2011), power commitments and demand for the 24 h of the next day are determined beforehand. In such a day-ahead market, there is a non-profit independent system operator (ISO) responsible for determining the LMPs and maintaining a regulated platform where market participants can submit supply offers or demand bids a day before. The power generators receive the posted LMPs from the ISO, and decide their generation amount to maximize their own utilities; (ii) For the aviation transportation system, to assure safe and high-quality service for travelers, we assume that the system is centrally monitored and controlled just like the current practice of the aviation industry, where E-UAVs’ tentative travel needs are submitted at least 24 h prior to the travels, and then the aviation agency assigns them with detailed routing and charging plans. Moreover, we assume that the E-UAVs of interest are owned by the individual travelers as personal vehicles (i.e., as a plausible business scenario in the near future), and we mainly focus on their applications for inter-city travels, where each trip requires a stop at one of the charging stations.[1] The short distance trips that do not need en-route charging are not included in this study, since the charging activities can be conducted at their origins and/or destinations (as part of the regular electricity loads there) and have little influence on either the charging stations (our focus of the study) or the travel plans. Moreover, due to the limited charging slots at charging stations, the agency would coordinate E-UAV users’ travel plans as well as the charging timing, such that the usage of charging slots does not exceed the capacity.

We propose a joint pricing scheme for the electricity market that accounts for the costs of both systems, such that system-wide

[1] The proposed modeling approach can easily be extended to more general cases where a single trip involves multiple or no charging stops. For the multiple-stop case, this can be done by evaluating (possibly through full or partial enumeration) the E-UAV users’ alternative routing decisions across charging stations (Adler et al., 2016), and adding the corresponding decision variables to the aviation agency’s optimization problem. The non-stop trips are not considered in this study, since they have no impact on other E-UAVs’ travel plans, and the charging at the origins or destinations (e.g., from users’ residential power outlets) can be directly included as base load to the power system (Zhang et al., 2017a).