Automation in Construction 68 (2016) 1–10

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Hybrid control algorithm for fuel consumption of a compound hybrid excavator

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ARTICLE INFO

Article history:
Received 30 July 2014
Received in revised form 3 March 2016
Accepted 26 March 2016
Available online xxxx

Keywords:
Compound hybrid excavator
Power management
Optimal control

ABSTRACT

The current paper describes a hybrid control algorithm for fuel consumption minimization of a compound hybrid excavator. The power train of the excavator integrates an engine assist motor, a super capacitor, and a dc/dc converter for hybridization of the original power train. This power train also incorporates an electrically propelled swing motor, which replaces the conventional hydraulic swing motor, to remove hydraulic loss and recuperate the kinetic energy of the swing motion. Since the super capacitor provides the required energy for the electric swing motor, sustaining the charge presents an important consideration in the power management algorithm design. First, the optimal control problem has been applied to the fuel consumption minimization problem, and an algorithm based on the equivalent fuel minimization strategy (ECMS) has been applied by analyzing the behavior of the co-state of the optimal control problem. The ECMS algorithm is integrated with an engine set speed regulator to increase the overall efficiency of the diesel engine. The engine set speed regulator was designed to change the engine set speed, depending on the engine load. Simulations show that the ECMS is near optimum compared to the dynamic programming results, maintaining an approximately 3% fuel improvement compared to a thermostat controller, which determines power distribution based on the state of charge. Excellent charge-sustaining performance was also achieved. The performance of the control algorithm was verified through real-world vehicle tests, resulting in an approximately 30% improvement in fuel economy, compared to the conventional excavator.

1. Introduction

The hybridization of construction vehicles has constituted an active topic of research since the 1990s. In particular, hybridization of excavators, one of the most widely utilized construction vehicles, is expected to result in substantial benefits because excavators' fuel costs comprise a considerable proportion of operating expenses. In addition, the attached electric motor can provide more traction power to hydraulic pumps; thus, hybridization can result in increased productivity.

The conventional excavator consists of a boom, an arm and bucket, and a hydraulic swing motor. This design allows for various types of hybridization, such as compound hybrid excavators, in which an electric motor substitutes for the hydraulic swing motor. The target excavator of the current paper, the compound, could represent the most promising configuration when accounting for development cost, reliability, and fuel economy [16].

Within the current paper, an optimal hybrid supervisory control algorithm, comprised of the power management control algorithm and the engine set speed control algorithm, has been proposed. The power management algorithm design is based on the equivalent fuel consumption minimization strategy (ECMS). The engine set speed algorithm was developed by modifying the behavior of the dynamic programming (DP). These two methods of the ECMS and DP-trained rule-based control are widely researched in the field of control of hybrid electric vehicles (HEV) [2–10]. The ECMS has achieved excellent fuel economy for various types of HEV; however, it is a heuristic approach and, therefore, near-optimal. The DP-based approach also shows fuel improvement close to the optimal solution, but performance could depend on the driving cycles.

Much research exists in the extant literature concerning hybrid excavators. For instance, Lee and Kwon investigated the fuel economy of various types of hybrid excavators [11–12]. Yoo, on the other hand, discussed the issues involved in developing compound hybrid excavators [1]. Furthermore, rule-based and fuzzy power management control algorithms are researched in [13–15]. Additionally, previous research has proposed DP-trained rule-based power management control and continuous engine set speed control [16]. However, the performance of the rule-based control could depend on load profiles, such as in HEVs. Furthermore, if the available energy from the secondary energy source is small, a charge-sustaining problem is created. The continuous engine set speed control could also generate undesirable fluctuations of

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http://dx.doi.org/10.1016/j.autcon.2016.03.017
0926-5805/© 2016 Published by Elsevier B.V.

engine speed during the excavation process. To overcome the drawbacks of previous research, an ECMS based on the optimal control problem and discretized engine set speed control strategy has been proposed. The simulations show that the fuel economy approaches that of the global optimal solution from the DP and guarantee excellent charge-sustaining performance. In addition, the performance of the proposed algorithm has been verified experimentally.

2. Compound hybrid excavator simulation model and dynamic programming

2.1. Compound hybrid excavator simulation model

The present paper utilizes the simulation model of the compound hybrid excavator developed in previous research [16]. The simulation model considers the hybrid power train of the target excavator but utilizes the detailed hydraulic system model. The dynamic response of the hydraulic system is considerably faster than that of the mechanical power train, and its effects on fuel analysis can be ignored. The simulation model employs a pre-calculated pump load and swing load, instead of a full hydraulic system dynamic model. Fig. 1 depicts the configuration of the compound hybrid excavator simulation model.

The target excavator's engine operates on the driver engine set speed, as shown in Fig. 2. When a driver sets the engine set speed, the fuel consumption rate of the diesel engine is regulated to track the engine set speed by the engine control unit (ECU). If the engine load increases, the ECU controls the fuel consumption rate to track the droop curve in Fig. 2, i.e., the ECU determines the fuel consumption rate by comparing the driver engine set speed and the current engine speed. In this case, the ECU has been modified. Fig. 3 depicts the diesel engine model, including the modified ECU. The diesel engine model has been validated utilizing engine dynamo test data. Fig. 4 presents the validation results. Peaks of engine speed in the simulation results in Fig. 4(a) appeared since the engine speed was affected by additional components, such as accessory devices connected to the engine. Since the engine speed control algorithm embedded in the excavator engine was unknown, the PI engine speed control algorithm was employed in our simulation.

The engine assist motor connects directly to the diesel engine and converts the mechanical energy to electric energy, and vice versa. The engine assist motor was modeled using a first-order transfer function

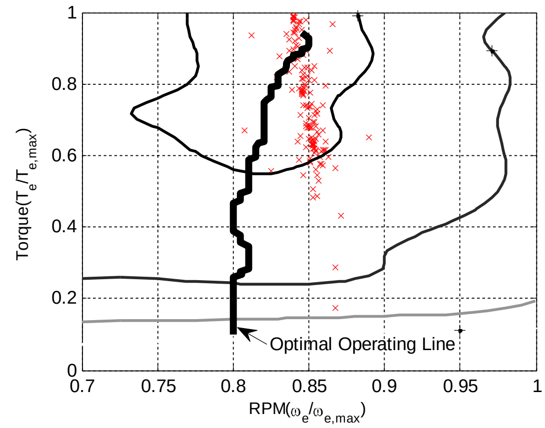

Fig. 2. Operating points and optimal operating line of diesel engine.

with a control delay. The power management controller, which controls the energy flow of the hybrid power train, determines the desired engine assist motor power.

The DC/DC converter controls the electric energy flow between the engine assist motor, the swing motor, and the super capacitor. The DC/DC converter controller regulates the DC link voltage to a constant value by compensating for the voltage drop due to the electric energy loss, using stored energy in the super capacitor. Since the DC/DC converter utilizes the stored energy of the super capacitor, the super capacitor voltage has been computed by considering the combined electric energy loss of the engine assist motor, the super capacitor, and the DC/DC converter.

2.2. Optimal fuel economy employing the dynamic programming technique

Previous research has employed dynamic programming (DP) to obtain the optimal fuel consumption of various types of hybrid power management problems mentioned in the literature [2–10]. DP results could provide insight for designing a power management algorithm, as well as serve as a benchmark for evaluating the performance of the designed power management algorithm. By applying the DP algorithm, the hybrid power train model of the target excavator has been effectively quantized and simplified.

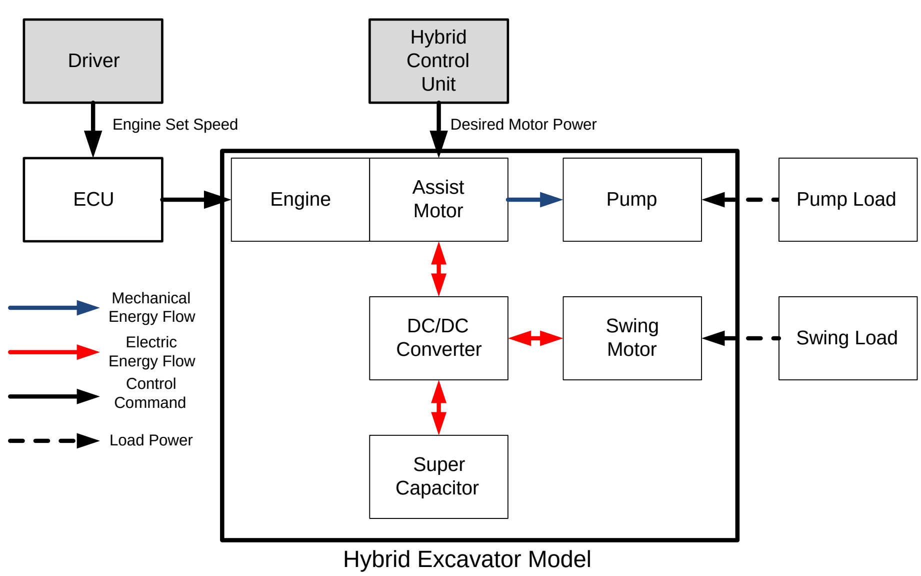

Fig. 1. Compound hybrid excavator.