

A Global Optimal Energy Management System for Hybrid Electric off-road Vehicles

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ABSTRACT

Energy management strategies greatly influence the power performance and fuel economy of series hybrid electric tracked bulldozers. In this paper, we present a procedure for the design of a power management strategy by defining a cost function, in this case, the minimization of the vehicle's fuel consumption over a driving cycle. To explore the fuel-saving potential of a series hybrid electric tracked bulldozer, a dynamic programming (DP) algorithm is utilized to determine the optimal control actions for a series hybrid powertrain, and this can be the benchmark for the assessment of other control strategies. The results from comparing the DP strategy and the rule-based control strategy indicate that this procedure results in approximately a 7% improvement in fuel economy.

Index Terms: Series hybrid electric tracked vehicle, power management strategy, dynamic programming, rule-based

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I. INTRODUCTION

Construction vehicles, such as bulldozers, running on diesel engines serve an important role in modern societies with tremendous infrastructural development. The increasing reliance on construction vehicles brings certain negative impacts such as energy unsustainability and poor air quality. In recent years, hybrid electric vehicle (HEV) technology has been proposed as the technology for new bulldozer configurations. In the United States, Caterpillar produced the first D7E hybrid electric drive tracked bulldozer in March 2008. Compared to traditional models, CO and NOx emissions were reduced by approximately 10% and 20%, respectively. The D7E can improve fuel economy by 25%. In this briefing, a new hybrid electric tracked bulldozer composed of an engine-generator, two driving motors, and an ultracapacitor (UC) is put forward, and this bulldozer boasts high-efficiencies and less fuel consumption compared to traditional ones. The topology of the powertrain under study is the one presented in Fig. 1. This hybrid electric tracked bulldozer uses an integrated controller to control two motors on both sides of the bulldozer independently and to transfer electric energy from the DC BUS into mechanical energy to drive the bulldozer. In this HEV, there are additional components, such as electric motors and an ultracapacitor, that provide more flexibility in the operation of the powertrain system to meet the driver's demand and minimize fuel consumption [1]. To fully realize the potential of the hybrid

powertrain, the power management function of these vehicles must be carefully designed. By power management, we mean the development of a higher-level control algorithm that determines the total amount of energy to be generated, and this power management system uses two power sources. In other words, the power management control is implemented in the vehicle-level control system to coordinate the overall hybrid powertrain to satisfy certain performance targets such as fuel economy [2].

Energy management strategies for HEVs can be roughly classified into four categories [3]. The first type is the numerical optimization method, where the entire driving cycle is taken into consideration and the global optimization is found numerically, an example of this include dynamic programming [4],[5],[6], model predictive control [7], [8], and stochastic dynamic programming [9]. Optimization approaches rely on analytical or numerical optimization algorithms which are, obviously, able to optimize the performance. The second approach is the analytical optimization method including Pontryagin's minimum principle and the Hamilton-Jacobi-Bellmann equation [10]. The third type is the equivalent consumption minimization strategy (ECMS), which was introduced by Paganelli et al. [11] as an approach that determines the optimal power split at each time instant rather than over a time horizon. The fourth type employs heuristic control techniques such as control rules/ fuzzy,

logic/ neural networks for estimation and control algorithm development [14], [15]. Heuristic strategies depend on a set of rules to determine the control action at each time instant. The rules are designed in accordance with intuition, human expertise, and/or mathematical models and, usually, without prior knowledge of the driving information. The heuristic method is popular and has been successfully applied in commercial HEVs such as the Honda Insight and Toyota Prius. However, its major disadvantage is that the overall efficiency of the powertrain is not optimal, and the emission control is not directly considered.

In this article, we apply the dynamic programming (DP) algorithm to solve the optimal power management problem of a series hybrid electric tracked bulldozer. Differing from road vehicles, the HETB is one kind of tracked vehicle. Obviously, the mechanical property is different from that of the HEV. Apart from the structural differences between HETB and HEV, their main difference lies in their working conditions. Unlike the HEV, the HETB's demand power changes dramatically between its soil-cutting stage and no-load stage under one certain drive cycle. Consequently, the MPC strategy's application in an HETB is more complicated than that in HEV. Furthermore, the drive cycle changes sharply according to the ground characteristic and even the weather condition in different working places. Thus, the MPC strategy's robustness is more important than that of HEV. Three scenarios were utilized to develop the energy management controller using the MPC. The first scenario is extracted from the typical working conditions of the bulldozer. The optimal solution over the typical drive cycle is obtained by minimizing the fuel consumption, and then, it is compared to the results gained from using a rule-based and DP power management strategies. As an approach that solves multi-step optimization problems based on Bellman's principle of optimality [16], DP provides a provably optimal energy management strategy through an exhaustive search of all control and state grids. Applying DP in this series hybrid electric tracked bulldozer consists of finding the optimal control sequences to obtain the optimal ultracapacitor's state of energy (SOE) trajectory and to minimize fuel consumption over a given driving profile. However, exact knowledge of the driving profile is seldom known in practice [17]. Nonetheless, the DP provides a benchmark to assess the optimality of other energy management strategies and improve the online strategy [18], [19], [20].

The remainder of this paper is organized as follows: In Section II, The series hybrid electric tracked bulldozer (HETB) model is described. The dynamic optimization problem and the DP procedure of the optimal control problem for this series HETB is formulated in Section III. The optimal results for the fuel consumption case are given in Section IV, followed by conclusion and future work in Section V.

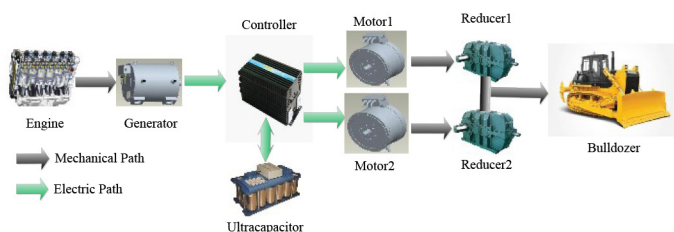


Fig. 1. The structure of the hybrid electric tracked bulldozer

II. SERIES HETB POWERTRAIN MODEL

A. System Configuration

The baseline bulldozer studied here is the SD-24 tracked bulldozer of Shantui Construction Machinery Co., Ltd, and its powertrain configuration is shown in fig.1. The series hybrid power system is composed of a diesel engine, ultracapacitor, permanent magnet generator, motor drive system, and tracks. A 2.4F ultracapacitor was chosen as the energy storage system. The hybrid electric bulldozer uses the integrated controller to control the motors on both sides of the bulldozer independently and to transfer the electric energy from the generator and ultracapacitor into mechanical energy to drive the bulldozer. The hybrid electric tracked bulldozer model is implemented in SIMULINK. For more information of the model, the reader is referred to [21].

B. The Vehicle Model

The movement behavior of the bulldozer along its moving direction is completely determined by all of the forces that act on it in the same direction. Distinguishing it from an ordinary vehicle, the major external forces acting on the two tracks in the longitudinal direction include the external travel resistance F_E and the operating resistance F_T . The aerodynamic drag and the acceleration resistance are neglected since the velocity of the bulldozer is very low.

$$F_E = F_c + F_b = \frac{2b}{(n+1)k^n} \left(\frac{G}{2bL} \right)^{\frac{n+1}{n}} + \gamma Z^2 b K_r + 2b Z c K_{pc} \quad (1)$$

$$\begin{aligned} F_T &= F_1 + F_2 + F_3 + F_4 \\ &= 10^6 B_1 h_p k_b + \frac{V \gamma \mu_1 \cos \theta}{k_s} \\ &\quad + 10^6 B_1 X \mu_2 k_y + G_t \mu_2 \cos \delta^2 \cos \theta \end{aligned} \quad (2)$$

where F_c is the compaction resistance (N); F_b is the bulldozing resistance (N); b is the track width (m); G is the vehicle weight (N); L is the track length (m); c is the soil cohesion coefficient (KPa); ψ is the soil internal friction angle ($^\circ$); n is the soil deformation index; k is the soil deformation modulus (KN/mⁿ⁺²); Z is the track amount of sinkage (m); γ is the unit weight (N/m³); and N_γ and N_c are the soil Terzaghi coefficients of the bearing capacity [22]. F_1 is the soil-cutting resistance (N); F_2 is the pushing resistance of the mound before the blade (N); F_3 is the frictional resistance between the ground and blade (N); F_4 is the horizontal component of the frictional resistance when the soil rises along the blade (N); k_b is the cutting resistance per unit area (MPa); B_1 is the blade width (m); h_p is the average cutting depth (m); G_t is the gravity of the mound in front of the bulldozing plate; μ_1 is the friction coefficient between soil particles; μ_2 is the friction coefficient between the soil and blade; θ is the slope ($^\circ$); V is the volume of the mound in front of the bulldozing plate; k_s is the loose degree coefficient of the soil; k_m is the fullness degree coefficient of the soil; H is the blade height (m); α_0 is the natural slope angle of the soil ($^\circ$); k_y is the cutting resistance per unit

area after the blade is pressed into the soil (MPa); X is the length of the worn blade contacting the ground (m); and δ is the cutting angle of the blade ($^\circ$).

By combing Equations (1) and (2), the vehicle torque requirements for the powertrain, T_{req} , can be formulated as:

$$T_{req} = \frac{r}{i_0 \eta} (F_E + F_T + m v) \quad (3)$$

Where, r is radius of the driving wheel; i_0 is the final gear ratio; η is the transmission efficiency; m is the vehicle mass; v is the vehicle drive speed along the longitudinal direction.

C. The Engine Model

Experimental data is used to generate the engine model. The fuel consumption map of the engine is expressed as the relationship between the crankshaft speed and power by a non-linear 3-D MAP constructed from experimental data as shown in Fig. 2.

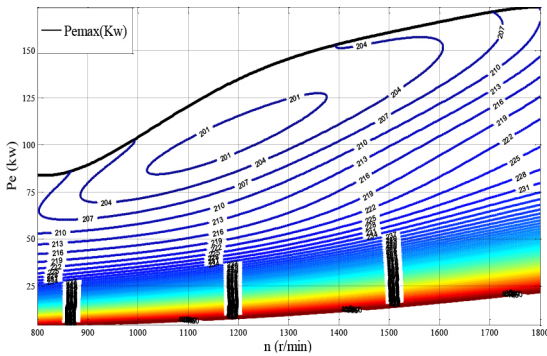


Fig. 2. Fuel consumption map of the diesel engine

The engine map represents the fuel consumption as a function of the mechanical power and speed. Assuming that it is possible to control the engine in order to make it operate at the fixed speed, the fuel consumption $\dot{B}_e$ (g/s) is a function only of the mechanical power delivered, P_e :

$$\dot{B}_e = \dot{B}_e(P_e) \quad (4)$$

The engine is constrained to operate within its limits:

$$\begin{aligned} N_{e,\min}(t) &\leq N_e(t) \leq N_{e,\max}(t); \\ P_{e,\min}(t) &\leq P_e(t) \leq P_{e,\max}(t); \\ T_{e,\min}(t) &\leq T_e(t) \leq T_{e,\max}(t); \end{aligned} \quad (5)$$

where $N_e(t)$ is the engine speed at time t ; $N_{e,\min}(t)$ and $N_{e,\max}(t)$ are the minimum and maximum speed of the engine at time t , respectively; $P_e(t)$ is the output power of the engine at time t ; $P_{e,\min}(t)$ and $P_{e,\max}(t)$ are the minimum and maximum output power of the engine at time t , respectively; $T_e(t)$ is the engine torque at time t ; and $T_{e,\min}(t)$ and $T_{e,\max}(t)$ are the minimum and maximum torque of the engine at time t , respectively.

D. The Generator and Motor Models

The generator and motor efficiency characteristics are expressed as a relationship between the speed and torque by a non-linear 3-D Map obtained from experimental data. The motor efficiency η_m at the operation point (n_m, T_m) is obtained from the following interpolation function:

$$\eta_m(n_m, T_m) = f(n_m, T_m) \quad (6)$$

where n_m is the speed of the motor, and T_m is the motor output torque.

E. The Ultracapacitor Model

The ultracapacitor pack is composed of several cells in both series and parallel modes. Each cell can be represented as a capacitance in series with a resistor. The capacitance models the ion accumulation; whereas, the resistance accounts for the electrolyte losses. The entire pack can be modeled by:

$$P_{uc}(t) = V_L(t) \cdot I_{cap}(t) \quad (7)$$

$$V_{cap}(t) = -\frac{1}{C} \int I_{cap}(t) dt \quad (8)$$

$$SOC(t) = \frac{Q(t)}{Q_{\max}} = \frac{CV_{cap}(t)}{CV_{\max}} = \frac{V_{cap}(t)}{V_{\max}} \quad (9)$$

$$SOE(t) = \frac{E(t)}{E_{\max}} = \frac{\frac{1}{2} CV_{cap}(t)^2}{\frac{1}{2} CV_{\max}^2} = \frac{V_{cap}(t)^2}{V_{\max}^2} = SOC(t)^2 \quad (10)$$

where P_{uc} is the output power of the ultracapacitor; V_L is the voltage at the terminals; I_{cap} is the current; V_{cap} is the voltage across the equivalent capacitance; $V_{\max}$ is the maximum voltage of the ultracapacitor; C is the equivalent capacitance of the ultracapacitor pack; SOC is the state of charge defined as the amount of charge stored in the capacitance $Q(t)$ relative to the maximum acceptable value $Q_{\max}$; SOE is the state of energy represents the amount of energy stored in the capacitance $E(t)$ relative to maximum energy capacity $E_{\max}$.

The state of energy is also relative to the maximum energy capacity and is related to the integral of the power, as shown in (11). Since the problem is set up using power balance equations, it is more natural to use the state of energy of the ultracapacitor as the most immediate control variable for the HETB. The variation of the SOE with respect to time is expressed using the following dynamic equation:

$$SOE(t) = \begin{cases} -\frac{1}{\eta_{cap}} \frac{P_{uc}(t)}{E_{cap}} & \text{if } P_{uc}(t) \geq 0 \text{ (discharge)} \\ -\eta_{cap} \frac{P_{uc}(t)}{E_{cap}} & \text{if } P_{uc}(t) < 0 \text{ (charge)} \end{cases}$$