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DESIGN AND TESTING OF A SMALL ORCHARD TRACTOR DRIVEN BY A POWER BATTERY

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KEYWORDS

electric tractor, orchard, drive system, dual motors.

ABSTRACT

An electric orchard tractor with a power battery and transmission driven by dual motors was developed. The output shafts of the walking and power take-off (PTO) motors are connected by a wet clutch, which controls whether the two motors are coupled or independent. When the load of the walking or PTO motor exceeds its output torque, the two motors are driven by power coupled by the wet clutch to meet the power demand. According to the heavy-load working conditions of ploughing and rototilling, the power battery capacity and working duration targets of 15 kW and 4 hours/charge were set. A prototype 15 kW electric orchard tractor was manufactured and assembled, and its performance was assessed. A bench test showed that the tractor's maximum PTO output power was 13.9 kW and a field rototilling test showed that its maximum continuous working time was 4.5 hours. Thus, the prototype electric orchard tractor met the design goals and requirements of for orchard operations.

INTRODUCTION

With concerns about and restrictions on carbon emissions throughout the world, many countries and regions have implemented stricter vehicle exhaust emission standards (Du & Ouyang, 2017; Xu et al., 2020;). Some agricultural operation sites, such as orchards and tea plantations, have strict requirements for powered machine emissions, with agricultural machinery expected to be pollution free to avoid fruit and tea contamination. These requirements are conducive to green food production and human health, and they make the use of electric agricultural machinery a good choice (Shiva et al., 2021; Moreda et al., 2016).

The tractor, as the main agricultural machinery operated on fruit and tea plantations, can equipped with various implements for tillage and plant protection operations. Research on electric tractors began at the end of the 19th century. In 1912, Siemens produced the first electric tractor, which had 50-hp power (Songhui et al., 2007); In the 21st century, with the gradual implementation of the Paris Agreement, the reduction of greenhouse gases has become a direct challenge in various industries. Electric tractor research and development has attracted the attention of many companies and universities, especially in recent years, and several high-powered purely electric tractors have been introduced. John Deere exhibited the SESAM, a lithium battery–powered 380-hp purely electric tractor, in 2016 (Yunhong, 2017) and launched a 680-hp electric driverless concept tractor in 2019 (Biddle, 2019). However, these tractors are very expensive and the energy density of their batteries is much less than that of fuel oil, which causes the technical bottleneck of short working times. For example, the SESAM takes 3 hours to charge fully for only 4 hours of work.

The capacity of an electric tractor to perform heavy-duty operations increases with its power, which requires significant increases in power battery weight and size. The battery energy density limits the tractor's full-load operation time. To solve this problem, John Deere developed the GridCON 400-hp cable-powered electric tractor, which has a cable turntable with 1000 m electric wire wrapped around it that connects directly to the civil power grid, in 2019 (Biddle, 2019). Obviously, the development of low- and medium-power purely electric tractors is a wise choice. For example, John Deere (2019) developed the 1E series of orchard tractors (John Deere, 2019). Ehime University developed a small four-wheel-drive electric tractor with 10-kW (Ueka et al., 2013). University of Ulsan in South Korea developed a 25-

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kW electric wheeled tractor (Yoo & Kim, 2013). Jiangsu University developed a 7.5- kW electric tracked tractor for facility agriculture (Liu & Xia, 2020). In 2018, Fendt introduced the 50-kW e100 Vairo, a purely electric multipurpose tractor for agricultural and municipal operations (Fendt, 2019). Monarch Tractor introduced a 29.4-kW purely electric tractor for orchard management operations (Visnic, 2021). For low- and medium-power orchard tractors used mainly for plant protection operations, the use of a power battery as the energy source can alleviate the problems of limited battery capacity and short operation times. More importantly, purely electric orchard tractors have the advantages of zero emissions and easy charging.

In this study, we designed, prototyped, and tested a purely electric orchard tractor with a 15-kW dual-motor drive. The development of the tractor's transmission system and controller is described in section 2. The power performance and fieldwork experiments conducted are detailed in section 3, and conclusions are presented in section 4.

MATERIAL AND METHODS

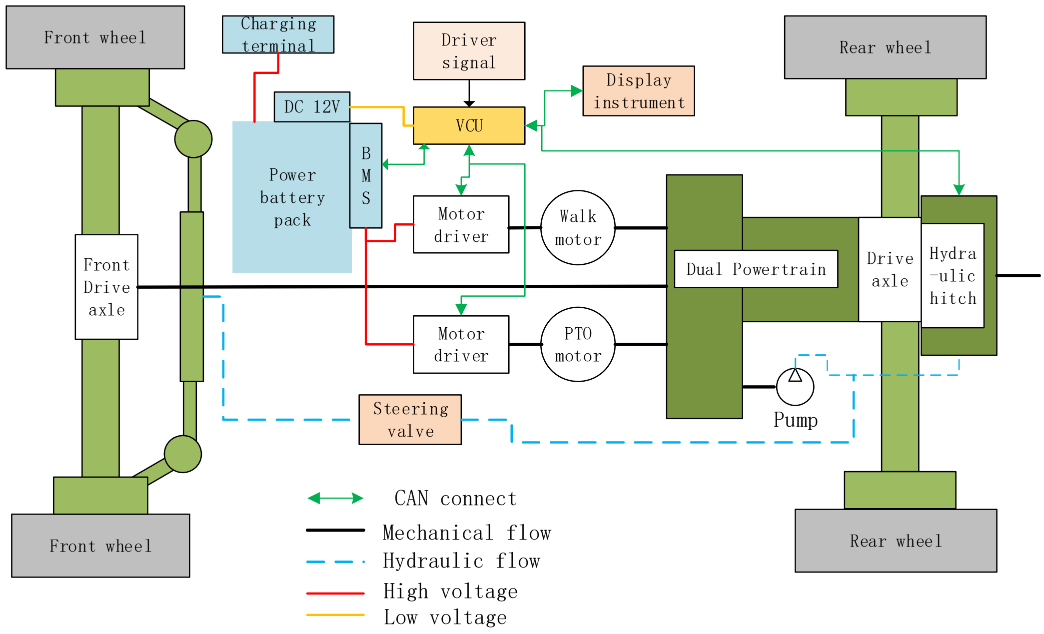
The electric orchard tractor scheme

According to the work demands for orchards and tea plantations, small orchard tractors should be able to perform cultivation, plant protection, and transportation tasks. Work parameters for electric orchard tractors are shown in Table 1. According to these parameters, walking drive traction, mechanical and hydraulic power outputs, and hitching capacity for farm implements are required.

TABLE 1. Work parameters for electric orchard tractors.

Ploughing	Width: 0.5 m Depth: 25 cm Speed: 5 km/h
Rotary tillage	Width: 1.1 m Depth: 15 cm Speed: 4 km/h
Transportation	Speed: 0-25 km/h
Plant protection	Speed: 4-8 km/h
PTO (power take-off)	760, 1000 r/min
Working time of one charge	> 4h

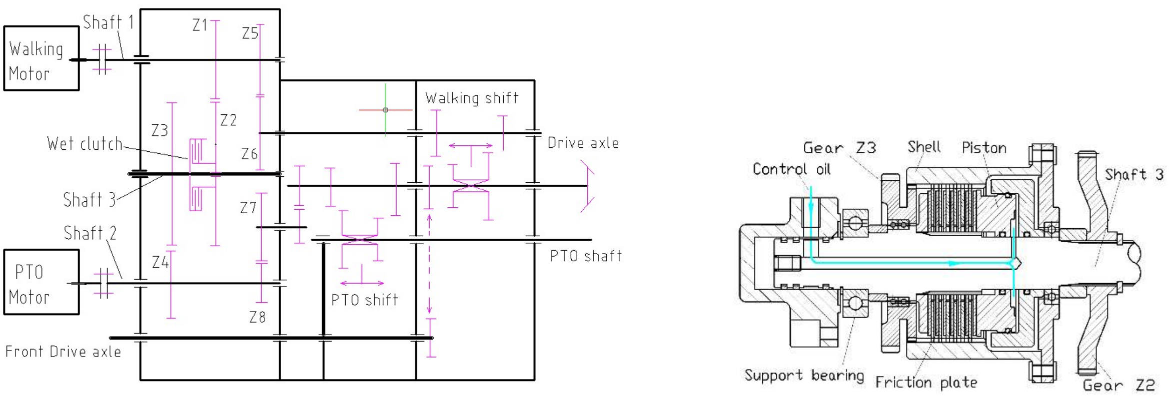
The detailed scheme of the electric tractor is shown in Fig. 1. The power source is the battery, and the driving component is a motor. Hydraulic power steering was adopted to improve portability. One motor drives the tractor's drive axle and the other realizes power take-off (PTO) through the transmission. The dual-motor drive scheme was adopted to resolve the contradiction between the need for stepless walking motor speed regulation and the stability of PTO to meet the standard output two speed (760 r/min,1000 r/min) during driving. The walking motor with the gears drives the walking system and meets the requirements for speed adjustment during transport and tillage. The PTO motor mainly meets the power requirements for a farm implement and for the hydraulic pump. To improve the tractor's working load capacity, the two motors are power coupled through a combination device. When the walking and PTO loads do not exceed the power of the respective motors, the walking motor drives the walking system and the PTO motor drives the power output shaft and hydraulic pump. When the traction load exceeds the power of the walking motor, the PTO motor outputs power to the walking system through the combination device to increase the tractive force. When the PTO load demand exceeds the PTO motor's capacity, the walking motor outputs power to the PTO system through the combination device. This dual-motor drive scheme improves the torque and power reserve relative to a single motor scheme.



CAN: Controller Area Network; VCU: Vehicle Contorl Unit; PTO:Power Take-Off

FIGURE 1. Structure of the dual-motor orchard tractor.

The tractor's transmission system is shown in Fig. 2. The walking motor is connected to input shaft 1 and the PTO motor is connected to input shaft 2 (Fig. 2a). The combination device is a wet clutch installed on the shaft 3, and gear Z2 connects its rear end. Gears Z1 and Z2 and Z5 and Z6, respectively, are engaged. Gear Z4 on input shaft 2 is engaged with gear Z3, which connects to the front end of the wet clutch. The wet clutch has no pressure between friction plates, the control oil does not exert pressure or push the piston, and the power of gear Z3 is not combined with that of gear Z2 (Fig. 2b). Under the working condition, the clutch is in a separation state. When the pressure between the friction plates is increased and exerted by the control oil to push the piston, and the power of gears Z2 and Z3 is combined. Under the working condition, the clutch is in a combination state. By controlling the separation and combination of the wet clutch, the combined and independent drives of the walking and PTO motors are realized.



(a) Transmission system (b) Operating principle of the wet clutch

FIGURE 2. Structure of the dual-motor power-coupling transmission system.

Three drive modes can be realized by controlling the wet clutch: torque coupling, independent walking motor operation, and independent PTO motor operation. The drive mode switching states are shown in Table 2.

TABLE 2. Dual-motor drive modes.

Drive Mode	Clutch	Walking Motor	PTO Motor
Coupling mode	Combining	ON	ON
Walking mode	Separating	ON	OFF
PTO mode	Separating	OFF	ON

Matching of battery energy and working load

According to the operating parameters listed in Table 1, the maximum output power of the electric orchard tractor is exerted under ploughing and rotary tillage conditions. Thus, the power required for these tasks was calculated separately, and the maximum was was taken as the rated power requirement for the tractor.

Calculation of the ploughing load

The tractor needs to overcome the tractive and rolling resistances of the wheels during ploughing; the air and acceleration resistances can be ignored because the walking speed is low. The force balance of the driving wheel (F_d) is expressed by [eq. 1]:

$$F_d = F_t + F_f, \quad (1)$$

Where:

F_t is the tractive resistance, and

F_f is the rolling resistance of the tractor wheels.

The tractive resistance during ploughing (F_x) can be estimated using the formula proposed in Standard D497.7 (ASABE, 2011) as follow:

$$F_x = F_i \cdot (A + B \cdot v + C \cdot v^2) \cdot W \cdot H, \quad (2)$$

Where:

F_i is the soil property coefficient (0.5 for orchard stubble field);

A–*C* are structural parameters related to the plough tool (A = 625, B = 0, and C = 5.1 for a ploughshare), the ploughing width W = 0.5 m;

v is the traction speed (km/h), and

H is the ploughing depth (cm).

The rolling resistance (F_f) can be calculated using the following equation:

$$F_f = m \cdot g \cdot f, \quad (3)$$

Where:

f is the wheel rolling resistance coefficient according to the orchard ground soil conditions (0.10 in the case);

m is the tractor mass (~900 kg), and

g is the acceleration of gravity. Substituting eqs (2) and (3) into [eq. (1)], F_d = 5585 N.

The maximum power output of the motor for ploughing (P) was calculated as:

$$P = K_h \cdot K_p \cdot F_d \cdot \frac{v}{\eta_m}, \quad (4)$$

Where:

K_h is the auxiliary dynamic coefficient for the hydraulic system (1.2);

K_p is the power reserve coefficient (1.2), and

η_m is the mechanical efficiency (0.85). Thus, P = 12.04 kW.

Calculation of the rotary tillage power

The rotary tillage power (P_t) was calculated using [eq. (5)] (CAAMAM, 2007):

$$P_t = 0.1 \cdot K_\lambda \cdot T \cdot v \cdot \frac{W}{\eta_m}, \quad (5)$$

Where:

K_λ is the soil rotary tillage resistance coefficient (4.01);

T is the rotary tillage depth (18 cm);

v is the tractor speed (5 km/h);

W is the rotary tillage width (1.2 m), and

η_m is the mechanical efficiency (0.85). The driving power (P_{f2}; for travel during tillage) was calculated using the following equation:

$$P_{f2} = m_t \cdot g \cdot f \cdot \frac{v}{\eta_m}, \quad (6)$$

Where:

m_t is the mass of the tractor (~900 kg);

g is the gravitational acceleration (9.8), and

f is the wheel rolling resistance coefficient (0.1). The output power for rotary tillage was calculated as:

$$P = P_t + P_{f2} = 12.5 \text{ kW}. \quad (7)$$

Thus, the output power of the electric tractor should be ≥ 12.5 kW.

Power battery pack capacity estimation

The continuous maximum-load operation time after a full charge was taken as the evaluation index for whole machine endurance. The battery output power (P_n) was calculated using the motor output power under maximum load (P_{max};12.5 kW), considering the energy conversion efficiency of the motor (n_m; 0.96):

$$P_n = \frac{P_{max}}{\eta_m}. \quad (8)$$

The value obtained was 13.49 kW. Under a continuous maximum-load operation time (t) of 4 h, the energy output of the battery pack (Q_0; J) was calculated as:

$$Q_0 = 3600 \cdot P_n \cdot t. \quad (8)$$

The battery pack capacity (C; Ah) was calculated as:

$$C = \frac{Q_0}{3600 \cdot D_\eta \cdot U \cdot n_t}, \quad (9)$$

Where:

U is the battery voltage (96 V for a lithium iron phosphate battery);

D_η is discharge efficiency of batteries (0.96), and

n_t is the battery-to-motor inverter efficiency (0.87). The C value of 718 Ah was obtained and rounded to 720 Ah to facilitate lithium battery pack manufacture.

Design of main motor drive system parameters

Transmission gear scheme

The electric orchard tractor must meet the requirements for transportation and low-speed operation in the field. As the energy conversion efficiency of the motor is high at high speed, but decreased at low speed, a two-speed gearing scheme was used. The high- and low-speed gears were designed for use during transportation and field operation, respectively. This approach maximizes operation in the high-speed range, thereby improving the motor's electric energy conversion efficiency.

Determination of motor rated power

Taking the calculated maximum motor drive power requirement of 12.5 kW and considering changes in and the complexity of tractor operating conditions, the optimal rated motor power was determined to be 15 kW (7.5 kW/motor). To ensure that the tractor was lightweight, three-phase asynchronous motors with small volumes and masses were selected. The main power system parameters for the electric tractor, based on the analysis described above, are shown in Table 3.

TABLE 3. Main parameters for drive system components.

Components	Parameters	Value
Motor	Rated power of single motor /kW	7.5
	Maximum output power/kW	15
	Rated rpm/(r/min)	3000
	Maximum rpm/(r/min)	3750
	Rated voltage/V	96
Battery pack	Voltage of single battery/V	3.2
	Rated capacity/Ah	720
Gearbox	High transmission ratio	29.14
	Low transmission ratio	56.84
Driving wheel	Radius/mm	468

Electric control system scheme

The tractor's electrical control system consists of a vehicle control unit (VCU), battery pack, battery management system (BMS), PTO and walking motors, and motor controller (Fig. 3). The VCU communicates with the BMS and motor controller by a controller area network (CAN), and with the speed pedal and clutch control valve via an input/output module. It receives the pedal speed signal from the driver and sends the command signal to the motor controller and clutch valve via a control algorithm to drive the walking and PTO motors.

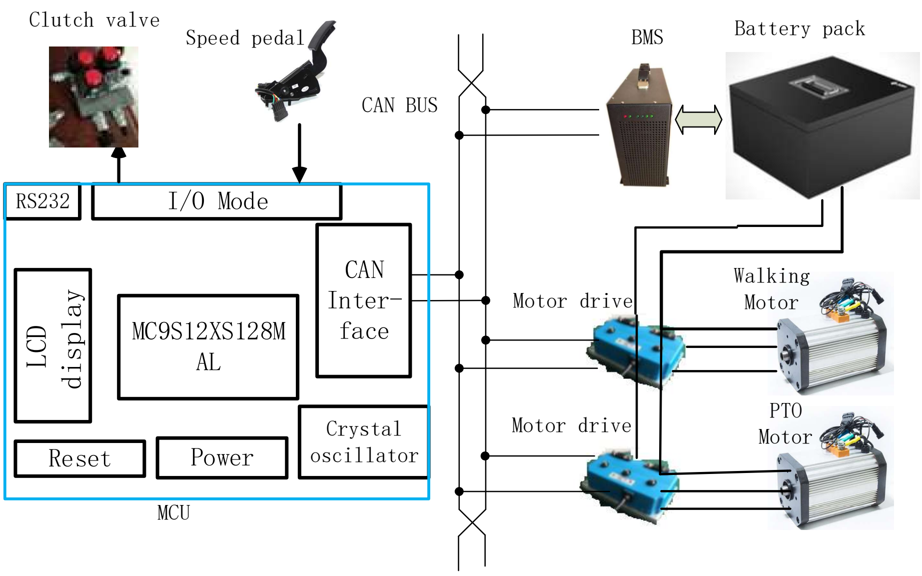


FIGURE 3. Structure of the tractor's electrical system.

Dual-motor control strategy

The dual motor control of the tractor is specified, as shown in Figure 4. The control algorithm includes single motor mode and dual motor mode. The single motor mode can controls the speed of the walking motor or PTO motor separately. When the output torque of the walking or PTO motor exceeds the rated torque, the dual motor mode was determined. In dual motor mode, the speeds of the walking motor and PTO motors are synchronized proportionally (according to the driving gear transmission ratio) and the clutch is engaged to realize power coupling output (Fig. 4). The controller calculates the motor speed target according to the electronic speed pedal signal, detects the motor current signal, judges whether the motor exceeds the rated torque, and adopts a single- or dual-motor working mode (Fig. 4). Then, it sends signals to the walking and PTO motors according to different operation modes to adjust their speeds to meet the traction requirement.

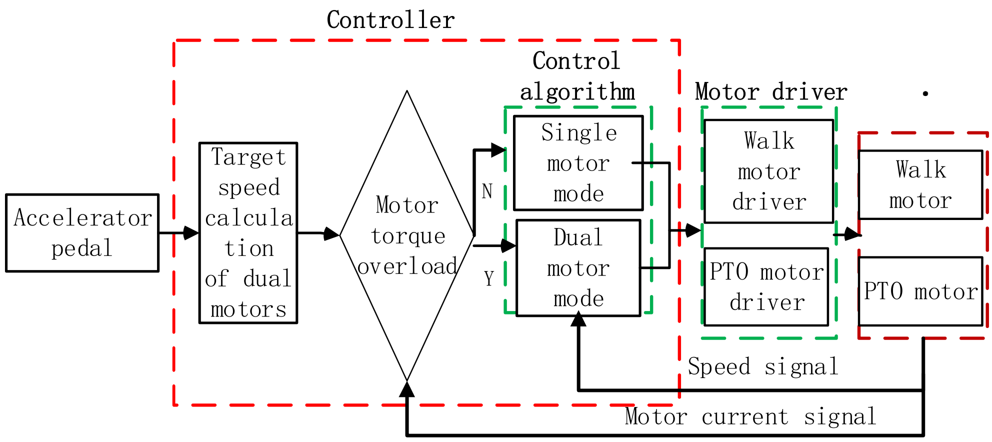


FIGURE 4. Schematic diagram of dual motor power control.

Manufacture and testing

A prototype electric orchard tractor was developed according to the above-described design scheme, including the selection of the motor, motor controller, and battery pack and the design of the frame, gearbox, and drive axle. After manufacture, the performance of the prototype was tested to determine whether it fulfilled the main target design parameters.

Prototype development and manufacture

A power battery meeting the capacity and voltage parameters was obtained from KXD Co., Ltd. (China, Shenzhen; model KXD-96V-720AH), and a battery management system was purchased from UDAN Technology Co., Ltd. (China, Hefei; A640). Motors with the maximum possible power mass ratio, smallest size, and structure suitable for fitting on a tractor frame was purchased from Xuzhou Jusong Electromechanical Technology Co., Ltd. (China, Xuzhou; JS-YS175-H75 three-phase induction motor). The rated power of this motor is 7.5 kW and its mass is 72 kg. A motor controller with a maximum current meeting the maximum peak motor current was obtained from Hercules Electric Co., Ltd. (China, Xian; EVC-550, maximum overload current = 400 A). The central processing unit of the vehicle controller was obtained from Freescale (MC9S12S128MAL). With these components, the design of the tractor chassis components, three-dimensional modeling, and assembly were performed (Fig. 5).

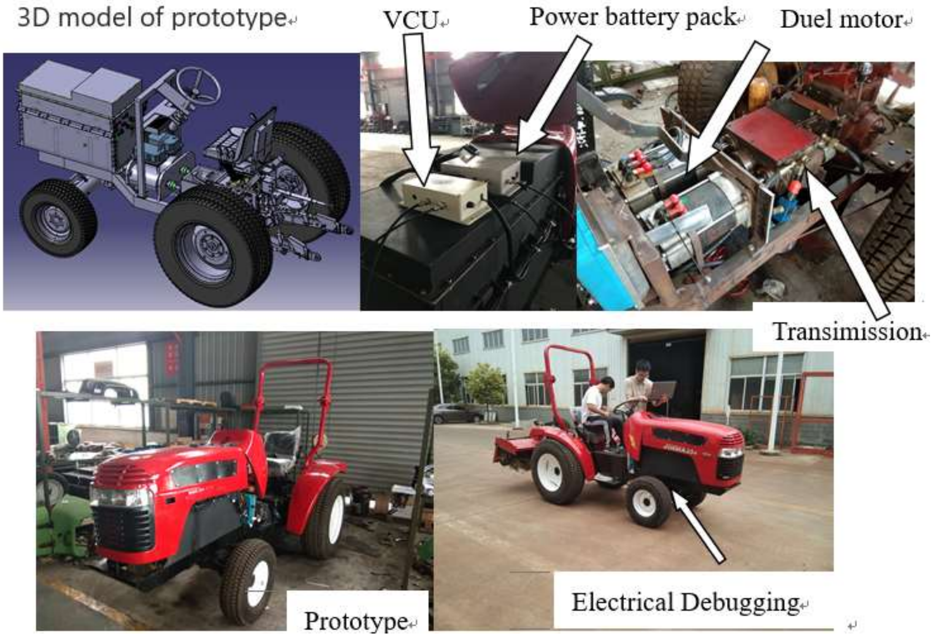
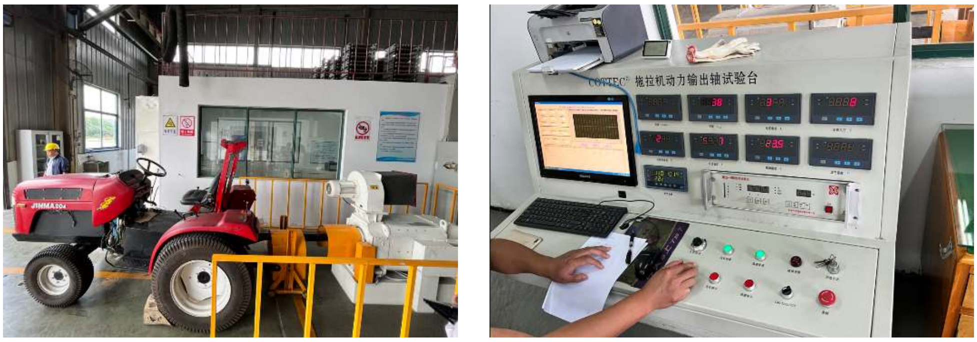


FIGURE 5. Electric tractor prototype with a dual-motor drive.

Prototype power output testing

After the debugging of the electrical control system and the transmission system, the prototype's power performance was assessed. According to the relevant tractor standard (ISO 789-1:2018, Agricultural tractors – Test procedures), the tractor's maximum output power was tested using the PTO shaft. The tractor was placed on a power output loading bench, and its maximum power output was tested in dual motor mode with a PTO shaft speed of 540 r/min (Fig. 6).



(a) PTO loading test (b) Dynamometer

FIGURE 6. PTO power test using a dynamometer.

The rated speed-power output characteristics of the electric motor were loaded using a dynamometer of PTO loading bench. The load was increased incrementally by 5 N•m after the stabilization of the PTO output speed until the tractor's power output speed was lesser than the rated output speed and within a constant range. This PTO power was taken as the tractor's maximum output power. The test was repeated three times, and the average value is 13.9 kW.

Prototype rototilling duration testing

The prototype was field tested to determine whether it met the target rototilling duration of 4 hours, used in the determination of power battery capacity. As the electric tractor needs to lift the attached agricultural implement when turning or reversing, continuous operation time of the power battery (t; h) was estimated:

$$t = \frac{1}{2}\left(\frac{5}{1 - C_1} + \frac{5}{0.1 - C_2}\right)\frac{0.9}{0.6}, \tag{10}$$

Where:

C_1 is the state of charge (SOC) after 5 minutes rototilling on a fully charged battery (high capacity), and

C_2 is the SOC after 5 minutes rototilling at 10% battery power (low capacity).

For the test, the BMS was connected to the charger until it indicated that the SOC was 100%. The prototype was then used to rototill soil in the field at a speed of 5 km/h and depth of 18 cm. After 5 minutes, C_1 was recorded. Other operations were performed until the SOC value was 10%.

Then, rototilling was performed for 5 minutes using the same parameters and C_2 was recorded (Fig. 7). Equation 10 was then used to estimate the field rototilling duration. The test was performed three times, and the average value of 4.5 hours was obtained (Table 4). This duration met the target for the electric orchard tractor.

FIGURE 7. Field testing of rototilling duration.

TABLE 4. Continuous rotary tillage time on a single charge.

Number of tests	No.1	No.2	No.3	Mean value
Operation time (hour)	4.51	4.64	4.36	4.50

CONCLUSIONS

In this study, a small electric orchard tractor was designed, including a dual-motor drive system and control schemes. The maximum power of dual-motor was determined as 15kW to meet load requirements for ploughing and rototilling. Based on a 4 hours continuous operation time, the capacity of the power battery is calculated and determined as 720 Ah. A chassis system was developed, and the electric tractor prototype was manufactured and assembled. The PTO power was determined to be 13.9 kW by bench testing, and the continuous operating time was determined to be 4.5 hours by rototilling field testing. These results show that the dual-motor drive scheme, power battery capacity, and power control scheme adopted were feasible.

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