Multi-objective Excavation Trajectory Optimization for Intelligent Electric Shovel Based on ROS

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Abstract. Electric shovel is a large-scale excavation equipment, which often suffer from discontinuous and inefficient excavation due to complicated mine condition. To address these challenges, a multi-objective optimization strategy for electric shovel is proposed to achieve an efficient, stable and intelligent operation. Firstly, the dynamical model of the electric shovel system is established based on Lagrange method. Then, the minimum energy consumption per volume and minimum relief angle difference are regarded as the optimization formulation considering multiple system constraints. Finally, the strategy is applied to the ROS-based intelligent prototype of shovel to verify the effectiveness. The results show that the multi-objective optimization strategy of the excavation trajectory has great guiding significance for the design of the intelligent electric shovel.

1. Introduction
Large-scale electric shovel is a large construction machinery, which is used to excavate coal, oil sands and other materials after blasting in open pit mines and load them onto excavation dump trucks for transportation. In order to meet the urgent needs of efficient excavation in open pit mines, large-scale and intelligent excavation equipment has become an inevitable trend. In industrial production, the excavation trajectory of conventional electric shovel is quite difficult, and the difference in productivity between different drivers is as high as 50% [1, 2]. The existing large-scale electric shovel relies only on manual experience to complete the excavation task, and does not have intelligent sensing and decision-making ability. It is urgent to build an intelligent system to complete the intelligent upgrade of the electric shovel. The intelligent research of electric shovel mainly consists of intelligent system and excavation trajectory planning. On the one hand, the excavation method using automatic trajectory planning can reduce the burden of the manipulators compared with traditional excavation. On the other hand, the automatic trajectory planning of the electric shovel can greatly improve the production efficiency and stability. Jud D et al. [3] realized the control of output force and running track of end-effector by using hierarchical optimization method, which effectively improved the precision of excavation process. Kim YB et al. [4] calculated the dynamic performance of the excavator using recursive geometric algorithm, and established a highly robust trajectory optimization algorithm based on the dynamic equation. Yoshida T et al. [5] used the discrete element method to establish a geotechnical model and parameterized the excavation trajectory to obtain the optimal excavation trajectory. Awuah-Offei et al. [6] used the energy consumed by the material with unit mass as the objective function and optimized the lifting and pushing speed of the excavator based on the dynamics. Frimpong et al. [7] used Newton-Euler method to establish a dynamic model, and predicted the best excavation performance based on the virtual prototype simulation. J. Seo et al. [8] introduced a excavation task planner that integrates the operational intelligence of construction planner and skilled operator into the robot control mechanism of automatic excavation system, which updates the
excavator parameters according to the three-dimensional model of the working environment and cognitive technology to generate the optimal excavation plan. However, most of the existing researches have dealt with excavation trajectory planning into single-objective deterministic optimization problems such as minimum excavation energy consumption. They are failed to comprehensively consider the trajectory planning from multiple perspectives such as efficiency and stability, so it is difficult to meet the application needs of intelligent excavators in the future.

To address the above issues, a multi-objective trajectory planning strategy with minimum energy consumption and minimum relief angle difference is proposed on the intelligent system of electric shovel, and then the optimal excavation trajectory considering multiple system constraints is optimized by the sequential quadratic programming (SQP) method. The planning strategy and intelligent system are applied to the scaled prototype to realize the intelligent test of the shovel, which provides a theoretical basis for the intelligent sensing, decision-making and driverless driving of the electric shovel.

2. System model

The intelligent electric shovel of this paper is to build the intelligent system on the 1:20 scale prototype of WK-55 excavator, as shown in Figure 1. The electric shovel usually consists of an upper component, a lower component, a working component and an intelligent system. The working component includes the stick, the lifting rope, the bucket, the boom and the balance wheel, which is the main operating mechanism for direct contact with the material and completing the excavation task. The upper assembly includes an electromechanical system consisting essentially of a lift motor, a push motor and a platform rotary motor. The most important functional component of the lower assembly is the track travel device. The excavation process of the electric shovel is mainly driven by the lift motor and the push motor to drive the lifting rope and the stick to complete the excavation work.

![Figure 1. Intelligent electric shovel model.](image-url)

2.1. Intelligent shovel system

With the rapid development of artificial intelligence and robotics, robot systems of different operating platforms have enabled developers to do a lot of repetitive work. As an open source system framework with distributed processing, strong code reusability and real-time communication of node messages, ROS is scalable in building shovel intelligent systems [9, 10].

The intelligent electric shovel system described in this paper is based on the ROS robot operating system and is designed with multiple sensors. Ubuntu and ROS systems are installed in the system to realize the robotization of the shovel. The sensing system acquires the shape parameters of the pile by the 3D Lidar scanner and sends it to the Industrial Personal Computer (IPC) for processing [11]. Then the optimal excavation speed parameters (ie motor control parameters) are calculated by the planning algorithm in the decision system and returned to the IPC, and the task command is send to the execution system by the IPC. The execution system is composed of the singlechip, the motor module and the sensor module to complete the task command. The motor module drives each motor to perform the corresponding actions and the sensor module returns the excavation status data to the IPC.
Moreover, the real-time communication and monitoring function of the electric shovel data flow is realized. The entire intelligent system monitors the real-time status information of the electric shovel excavation process as comprehensively as possible, as shown in Figure 2.

![Figure 2. Real-time status of intelligent shovel system.](image)

2.2. Dynamic model

The dynamic model of the working device of the intelligent electric shovel model described in this paper is shown in Figure 3. Suppose τ is the output torque of the working device, M is the inertia matrix of the working device, C is the centripetal force and the Coriolis matrix, and G is the gravity vector. Then the Lagrange equation of the shovel’s working device is shown in (1).

\[
M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = \tau
\]

(1)

The working device of the electric shovel is in a vertical plane only during the excavation process, regardless of the rotary motion of the turret. To simplify the working device into a two degree of freedom manipulator, the dynamic equation can be established as (2) and (3).

![Figure 3. Analysis of working device of shovel](image)

\[
\begin{align*}
(m_b + m_d)(r^2 - L_b r + \frac{1}{3} L_b^2) + m_d (r^2 + L_d r + \frac{1}{3} L_d^2)\ddot{\theta} + [2(m_b + m_d)\dot{\theta} \cdot r - (m_b + m_d)g \sin \theta \cos \theta - m_c \dot{\theta} \cdot (L_d + r)] &= 0 \\
= F_r \cdot r \cdot \sin \theta - F_L \cdot (L_d + r) \\
(m_b + m_d)F_r \cdot [m_b \cdot \dot{\theta} \cdot r - \frac{1}{2} (m_b L_b - m_d L_d)\dot{\theta}] + m_d g \sin \theta (r + \frac{L_d}{2}) - (m_b + m_d)g \cos \theta &= F_h - F_n - F_r \cdot \cos \theta 
\end{align*}
\]

(2) and (3)
Where \( m_b \) and \( m_d \) represent the mass of the stick and the bucket respectively, \( L_b \) and \( L_d \) represent the length of the stick and the bucket respectively, \( \theta \) represents the rotation angle of the stick relative to the vertical line, and \( r \) is the distance that the stick slides during the movement, \( g \) represents the gravitational acceleration constant. The main working parameters of the prototype are shown in Table 1 below.

### Table 1. Working parameters of shovel proportional prototype.

| Parameters/unit | Value     | Parameters/unit | Value     |
|-----------------|-----------|-----------------|-----------|
| \( V_c \)/m³    | 0.068     | \( H \)/m       | 0.447     |
| \( L_b \)/m     | 0.520     | \( \rho \)/kg/m³ | 1700      |
| \( L_d \)/m     | 0.165     | \( m_b \)/kg    | 8         |
| \( w_d \)/m     | 0.245     | \( m_d \)/kg    | 4         |
| \( R \)/m       | 0.050     |                 |           |

### 3. Multi-objective trajectory optimization strategy

In order to achieve fast, stable and efficient excavation work, based on the Lagrange method to establish the dynamic equation, the minimum energy consumption and the minimum relief angle difference are taken as the objective functions, and the constraints such as the full bucket rate, motion parameters and system physical parameters are considered. Using the point-to-point trajectory planning method, the mathematical model of the excavation trajectory is transformed into an n-order polynomial function by discretizing the time domain [12, 13]. Furthermore, the traditional optimal control problem is changed to directly solve the optimal control parameters, and the optimal excavation trajectory is obtained by solving the optimal control parameters.

#### 3.1. Determination of objective function

a. The minimum energy consumption of a single excavation cycle is taken as the first objective function.

\[
 f_1(x) = \min \frac{E}{V} 
\]

The first function and the total energy consumption can be formulated as (4) and (5).

\[
 E = W_r + W_c
\]

b. The minimum relief angle difference of the excavation process is taken as the second objective function.

The second function can be formulated as (6).

\[
 f_2(x) = \min[\beta_{\max} - \beta_{\min}] 
\]

c. The above objective function is weighted and averaged, the multi-objective problem is transformed into a single-objective problem. Then the total optimization objective function can be obtained using (7).

\[
 f(x) = w_1f_1(x) + w_2f_2(x) 
\]

#### 3.2. Constraints

a. Full bucket rate constraint

The intelligent excavation must at least ensure that the full bucket rate is above 90% and cannot be too large. If the full bucket rate is too large, the motor energy consumption will be increased. Therefore, the maximum limit for selecting the full bucket rate is 110%, as shown in the formula (8).

\[
 0.9V_c \leq V \leq 1.1V_c 
\]

b. Motion parameters constraint

During the excavation operation, the cutting angle of the bucket of intelligent electric shovel changes at a constant time and within a certain range, that is illustrated in (9).

\[
 \beta_{\min} \leq \beta \leq \beta_{\max} 
\]

The excavation process is mainly carried out by the lifting motor and the pushing motor jointly driving the bucket, and the speed of the pulling rope and the pressing rod should be greater than 0, that is (10).
\[
\begin{align*}
    v_i &\geq 0 \\
    v_c &\geq 0
\end{align*}
\]  
(10)

c. Physical parameters constraint

The effective radius of the pushing process should be limited by the maximum size of the stick, which is the formula (11).

\[ r \leq L_b \]  
(11)

In order to ensure the smooth completion of the excavation process, the bucket teeth should be higher than the height of the pair after the excavation work is completed, which is the formula (12).

\[ H \leq y_f \]  
(12)

Through the dynamic model of the shovel robot established in Section 2.2, the sequential quadratic programming method (SQP) is used to solve the nonlinear problem with multiple constraint conditions, and the trajectory planning of the shovel robot along the given polynomial curve equation is realized. The SQP method is a solution to the constrained optimization problem. It is effective for solving the nonlinear optimization problem, and it has good convergence, high computational efficiency and strong boundary search ability. It is more prominent than other optimization algorithms in real-time trajectory planning, and is suitable for intelligent systems.

4. Simulation and experimental results

Take the scale of the smart shovel as an example. The operating system is Ubuntu16.04 and ROS (kinetic). The intelligent system and the excavation trajectory multi-objective optimization strategy were applied to the proportional prototype to carry out the experiment. The sampling frequency was 10 Hz. At the same time, the vibration of the boom in different directions during the excavation process was described by the data of the three-axis accelerometer in the sensor module. The specific experimental process is shown in Figure 4, which mainly includes the initial position, excavation process, rotation and unloading process, and finally returns to the initial position. The material is made of general-purpose loose sand.

![Figure 4. Experimental process of intelligent prototype.](image)

4.1. Comparison of manual and automatic test results

The scale prototype of the intelligent electric shovel studied in this paper is designed into two modes of operation: manual excavation and automatic excavation. The manual excavation process is performed by the operator through the remote control handle to control the lifting motor, push motor and other components. Automatic excavation is to first sense the external environment through laser radar, and then calculate the corresponding excavation parameters by internal decision algorithm to control the corresponding motor to perform the excavation operation.

Under the premise that the operator can skillfully carry out the excavation work, the excavation tests in different modes are performed on the piles of the same pile angle. As can be seen from Figure 5, even the skilled operators have certain differences in each excavation, and the automatic excavation mode using the optimal trajectory planning strategy is basically the same and the excavation process is smooth and stable. Figure 6 shows that for the manual mode in the excavation process, the lifting motor power is not much
different from the automatic mode, but the manual mode is much larger than the automatic mode for the power of the push motor. This result may be due to the difficult operation of the linkage of the joystick during manual excavation. In theory, in the working process of the extra-large excavation electric shovel, the power of the lifting motor is greater than that of the pushing motor, indicating that the lifting rope plays a major role in the operation process, the results of the automatic excavation test are consistent with the theoretical results. As can be seen from Figure 6, the automatic excavation process time is about 12 s, and the manual excavation process completed by the skilled operator is about 15 s and it is difficult to maintain consistency, which indicates that the excavation efficiency of the automatic excavation is high.

Table 2. Analysis of results in manual and automatic mode.

| Mode    | Full bucket rate | Energy consumption per volume(kJ/m^3) | Std of accelerometer(m/s^2) |
|---------|------------------|--------------------------------------|-----------------------------|
| Manual  | 0.85             | 29.72                                | 2.59 3.35 0.29              |
| Automatic | 0.95            | 25.10                                | 2.43 2.66 0.37              |

The experimental results from Table 2 show that the excavation energy consumption of excavation mode with optimization strategy is lower, and the energy consumption per unit volume excavation in automatic excavation process is reduced by 18.41% compared with manual excavation. Manual excavation has a large difference in the full bucket rate due to the operator's human factors, and the average full bucket rate is 0.85. The average value of the automatic excavation full bucket rate is 0.95. Obviously, the automatic bucket mode has a higher full bucket rate. The vibration accelerations of the X, Y and Z axes in the automatic excavation mode are smaller than the manual excavation, which can effectively reduce the vibration of the shovel boom. The reason may be that the control of the motor in the automatic excavation mode is more stable and reduces the excavation. The impact of the impact load during the process.

4.2. Results of single-objective and multi-objective experiments
When $w_2=0$, $w_1=1$, this is the single-objective optimization problem that objective function is determined only by the minimum energy consumption per unit volume of material. When both $w_1$ and $w_2$ are not 0, this is a multi-objective optimization problem that considers the minimum energy consumption and the minimum relief angle difference. In this paper, when considering the influence of excavation time, vibration and other factors, the excavation trajectory is processed into a multi-objective optimization problem, and a sequential quadratic programming method is introduced to optimize the coefficients of polynomial excavation trajectory and obtain the optimal excavation trajectory. Then, the multi-objective and the single-objective optimization problem are respectively applied to the test of the intelligent shovel prototype.

Figure 7 and Figure 8 above show the theoretical and actual excavation trajectory curves for single-objective and multi-objective optimization under different pile-up angles. It can be seen that the actual test
results are consistent with the theoretical results, and the excavation trajectory is steeper as the angle of the pile is increased.

Taking the test results of the material with a stack angle of 40 degrees as an example, Figure 9 shows that the single-objective and multi-objective optimization of the motor power trend is consistent, but the instantaneous power of multi-objective optimization strategy is slightly larger than that of single-objective in the middle of the excavation process. There is little difference between the start and end stages of excavation.

The data in Table 3 shows that the energy consumption per unit volume of the multi-target strategy is slightly higher than the single target. However, the maximum post-excavation angle difference of the multi-target strategy is 0.38 rad, which is smaller than the single-target strategy, and the stability of the excavation process is improved to some extent. The stability can be expressed by the vibration data of the boom. Under the multi-objective strategy, the standard deviation of the acceleration of the boom in the X and Y directions is smaller than that of the single target strategy, and the Z direction is basically the same, indicating that the multi-objective optimization strategy can reduce the vibration of the boom during the working process.

**Table 3. Analysis of excavation test results under single objective and multi-objective optimization**

| Mode      | Relief angle difference(rad) | Energy consumption | Std of accelerometer(m/s²) |
|-----------|-----------------------------|--------------------|---------------------------|
|           |                             |                    |                           |
Due to the practical environment and complicated working conditions of the large electric shovel, the whole machine or local abnormal vibration often occurs, which may easily cause wear failure or fatigue failure of the bearings, gears and other transmission parts, and even broken shaft, boom bending and other serious accidents. It is necessary to reduce vibration of the shovel. Considering the energy consumption and vibration factors comprehensively, although the energy consumed by the single-objective strategy is lower, the vibration is larger. Relatively speaking, the multi-objective strategy is more conducive to prolonging the life of the gear rack, bearing and other equipment of the machine. It is beneficial to improve the performance of the whole machine.

5. Conclusion
Taking the proportional prototype of ROS-based intelligent electric shovel as the research object, a multi-objective optimization strategy based on the minimum energy consumption per volume and the minimum relief angle difference is proposed and tested. This strategy reduces the energy consumption of the whole system. It ensures the stability of the excavation process, and reduces vibration to extend the life of the machine and improves the performance of the whole machine.

(1) Through the optimal control of the intelligent electric shovel excavation trajectory, not only the shovel intelligent decision-making excavation process can be realized, but also the energy consumption of the whole process can be greatly reduced, and the excavation efficiency and operation safety can be significantly improved compared with the traditional manual operation.

(2) Comparing the multi-objective and single-objective optimization strategies of the excavation trajectory, the energy consumption and vibration factors are comprehensively integrated, and the stability of the excavation process under the multi-objective strategy has been greatly improved, which is more conducive to extending the life of the whole machine.

(3) Changing the weighting coefficient and physical constraints of the multi-objective optimization objective function, the optimization objective can be adjusted for different complex working conditions to adapt to the intelligent operation of the electric shovel in the practical environment.

6. References
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Acknowledgments

The research is supported by National Natural Science Foundation of China (Grant No.U1608256).