Optimal technological process planning approach based on the state of mechatronic systems

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Abstract. The article presents the problem formulation for diagnostics and optimal planning of the trajectory of the technological process taking into account the wear of the mechatronic systems and its electric motors. As an example, we consider a mobile robot with a differential drive, which must successively pass a field of various shapes. The trajectory of movement is chosen taking into account the wear of its electric motors. To solve this problem, it is supposed to use graph theory and probabilistic algorithms. Examples of solutions to the problem are given without taking into account the properties of the soil in the working space of the robot, used by the type of drive and its angle of rotation. The power of sets of feasible solutions will increase significantly with increasing number of technological operations, which, in turn, will lead to inefficiency of using brute force methods for solving the formulated problem and the need to solve it based on probabilistic algorithms agent metaheuristics.

1. Introduction

The reliability of industrial enterprises largely depends on the state of electric power equipment, ensuring long-term uninterrupted operation of the technological chain, an unplanned shutdown of which can lead to serious accidents, resulting in long downtime and significant financial losses. The main consumer of electricity in the world is electric motors, ensuring the reliability and safety of operation of which dictates the need to estimate the spent resource of responsible structural components and to analyze the rate of damage accumulation at these nodes during operation.

The main types of faults that occur in electric motors during their operation are damage to the insulation of the armature windings (50%). This can be: breakdown of insulation (30%), overheating (26%) and mechanical damage (20%). The causes of accidents are caused by normal physical aging and wear (34%), poor lubrication (15%), increased humidity (10%), and faults detected during the inspection (30%) [1]. Also, a significant impact on the life of electric motors have loading conditions during operation, the management of which will significantly extend the uptime of the electric drive and the equipment as a whole [2,3]. Therefore, to solve the problem of improving the reliability of the electric motor separately from the object on which it is installed without taking into account the operation of all other mechanisms is not possible. Therefore, this task should be solved for a group of drives of an object operating in a certain technological process.

An example of the object of research is a mobile robot with four independent electric drives, which are a mechatronic module "motor-wheel" [4]. The robot is used for the needs of agriculture and moves over rough terrain. The task of the robot is the implementation of the technological process / detour of the field of a given geometry [5,6]. In this case, the choice of the trajectory of the robot (the sequence of technological operations of the movement, which determine the technological process of the field processing) should be carried out in such a way that the wear of the drives of its wheels is minimal.

2. Robot wear model

In figure 1 shown model of a four-wheeled mobile robot with a differential drive. It is assumed that the robot is driven in one of three ways:
1) using the wheels $D^1$ and $D^2$ (front wheel drive);
2) using the wheels $D^3$ and $D^4$ (tasks drive);
3) using all four wheels simultaneously (all-wheel drive).

\[ P(t_i) = p^1 + p^2 + p^3 + p^4, \]

where $p^1$, $p^2$, $p^3$, $p^4$ is the degree of wear when performing a single technological operation of the drives $D^1$, $D^2$, $D^3$, and $D^4$, respectively.

The degree of wear of the robot is the sum of the degrees of wear of the drives of each wheel when performing a single technological operation $t_i$ (1).

At the same time, the wear of the electric drive of each of the wheels for an individual technological operation is determined as a function of three arguments (2):

- $k_{ground}$ – variable that determines the properties of the soil (takes on the values: 1 - smooth hard surface, 2 - smooth loose surface, 3 - uneven loose surface);
- $t_{fan}$ – A variable defining the mode of operation of the engine (0 - passive, 1 - in the “full drive” mode, 2 - in the active front or rear drive mode);
- $M_{turn}$ - variable that determines the additional load on the motor when performing a turn (for each drive, turns are taken into account as follows: for drives $D^1$ and $D^3$ - to the right, for $D^2$ and $D^4$ - to the left).
3. Reasoning

For experiments in the proposed model of wear, the following restrictions are introduced:

1) the robot moves on a horizontal surface and the Z coordinate is taken constant \((Z=\text{const})\);
2) the robot moves at approximately constant speed when performing all technological operations that determine a separate technological process \((V=\text{const})\).

For the organization of the technological process a specific field is created (the working space of the robot) that has a certain flat geometry / configuration (some of the possible options are shown in Figure 3.a \((n = 3)\), 3.b \((n = 4)\), 3.c \((n = 15)\) and 3.d \((n = 14)\)). Processing such a field is a separate process.

\[
\begin{align*}
\begin{cases}
p^1 = f(k^1_{\text{ground}}t^1_{\text{fun}}, M^1_{\text{turn}}), \\
p^2 = f(k^2_{\text{ground}}t^2_{\text{fun}}, M^2_{\text{turn}}), \\
p^3 = f(k^3_{\text{ground}}t^3_{\text{fun}}, M^3_{\text{turn}}), \\
p^4 = f(k^4_{\text{ground}}t^4_{\text{fun}}, M^4_{\text{turn}}).
\end{cases}
\end{align*}
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\[ \sum M_{\text{turn}(R)} - \sum M_{\text{turn}(L)} \rightarrow \min . \]  

If for a particular field all its \( n \) segments (which define a certain technological process in the aggregate) are represented as the corresponding graph \( T(V, E) \), the set of vertices of which \( V \) uniquely correspond to the field segments, and the set of edges \( E \) logically define possible transitions between adjacent segments (technological operations), the mathematical problem of the synthesis of an efficient trajectory \( G(P_0) \) for the technological process of field processing can be represented as (1), (2), (4) and follows (5) [7,8]:

\[
G(P_0) = \left\{ t_i \mid f(t) = \sum_{i=1}^{n} P(t_i) \rightarrow \min, \ i = 1..n \right\}, \ Z = \text{const}, \ V = \text{const} .
\]  

4. Solution

Variants of graph representation for partitions of working space of robot (fig. 2.a, 2.b, 2.c and 2.d) are shown in figures 3.a, 3.b, 3.c 3.d respectively.

\[ \begin{align*}
  \text{a)} & \quad \begin{array}{c}
  t_0 \quad t_11 \quad t_2 \quad t_3
  \end{array} \\
  \text{b)} & \quad \begin{array}{c}
  t_0 \quad t_11 \quad t_2 \quad t_3 \quad t_4
  \end{array} \\
  \text{c)} & \quad \begin{array}{c}
  t_0 \quad t_11 \quad t_2 \quad t_3 \\
  t_4 \quad t_5 \quad t_6 \quad t_7 \\
  t_8 \quad t_9 \quad t_{10} \quad t_{11}
  \end{array} \\
  \text{d)} & \quad \begin{array}{c}
  t_0 \quad t_11 \quad t_2 \quad t_3 \\
  t_4 \quad t_5 \quad t_6 \quad t_7 \\
  t_8 \quad t_9 \quad t_{10} \quad t_{11} \quad t_{12} \quad t_{13} \quad t_{14} \quad t_{15} \quad t_{16}
  \end{array}
\]

**Figure 3.** Variants of the graph representation of the workspace of the robot

Possible solutions for these cases shown in figure 3.a \( (G(P_0) = \{t_0, t_1, t_2, t_3\}) \) and 3.b \( (G(P_0) = \{t_0, t_1, t_2, t_3, t_4\}) \) are obvious. For more difficult case as in figure 3.c, solution will have form, for example \( (G(P_0) = \{t_0, t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_9, t_{10}, t_{11}, t_{12}\}) \), and for the most difficult case as in 3.d, solution will have form, for example \( (G(P_0) = \{t_0, t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_9, t_{10}, t_{11}, t_{12}\}) \).
To demonstrate the turns within the selected trajectories, we define the turn matrixes $G(M_{\text{turn}})$. To do this, we use the following notation: 0 - turn within $t_i$ (not performed), 1 - as part of the technological operation, turn right ($M_{\text{turn}(R)}$), 2 - turn left ($M_{\text{turn}(L)}$). Then the matrix $G(M_{\text{turn}})$ for each of the four previously defined trajectories will take the following form:

- for the 1st trajectory: $G(M_{\text{turn}}) = \{0,0,0,0\}$;
- for the 2nd trajectory: $G(M_{\text{turn}}) = \{0,0,1,0,0\}$;
- for the third trajectory: $G(M_{\text{turn}}) = \{0,0,0,1,0,0,2,0,0,1,0,0,0\}$;
- for the 4th trajectory: $G(M_{\text{turn}}) = \{0,0,1,2,0,0,2,2,1,1,0,2,2,0\}$.

The selected trajectory can be considered optimal from the standpoint of minimum engine wear if the number of left and right turns for the indicated options of trajectories $G(P_0)$ approximately/conditionally coincides.

It is important to note that the presented examples of solutions to the problem (5) are given without taking into account the properties of the soil in the working space of the robot, used by the type of drive and its angle of rotation. The solution of these problems will be carried out in the framework of further research.

5. Conclusion

Obviously, in this case, the power of sets of feasible solutions will increase significantly with increasing number of technological operations, which, in turn, will lead to inefficiency of using brute force methods for solving the formulated problem and the need to solve it based on probabilistic algorithms (for example, agent metaheuristics). [9, 10, 11].

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