Automation of operation procedure of a wheeled mobile machine

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Abstract. The article discusses the theoretical foundations of automation of operation procedure of a wheeled mobile machine. The basis of equations system describing the performance “lane change” maneuver is a combination of the main types of maneuvers: correction of sidewise displacement and angularity deviation, as well as trajectory curvature. The equations system describes the entire process of executing “lane change” maneuver, taking into account peculiarities of entering and recovering from the maneuver. On the basis of the proposed equations system, the recommended form of the control action is presented when performing the “lane change” maneuver. The proposed algorithm for the control activity implementation was tested in the process of field-control tests’ performance of the K-701 wheel-tyre tractor with the hinged frame. The results of field-control tests show that the proposed control model can be used when carrying out certain types of field-control tests that do not require the significant precision of performance.

Simulation of various processes during the movement of a mobile machine is covered in a number of studies, such as V.Mikhailov [1], A. Lepeshkin [2], V.Vasilchenkov [3] and S.Ostashevsky [4] studied the operation procedure of a mobile machine.

Automation of operation procedure of a mobile vehicle supposes replacing of such an important link in the “Driver – Car – Road – Environment” system as a driver to a smart drive that stimulates control action according to a certain algorithm. The control algorithm should include the reproduction of the path of motion in the process of car movement.

The main types of mobile machine motions are: “linear”, “rotary”, “snake-like”, “lane change”.

Conducted researches [5] showed that any movement of a wheeled mobile vehicle can be obtained by combining 3 main types of manipulation:
- correction of sidewise displacement;
- correction of angularity deviation;
- correction of trajectory curvature.

The purpose of this study is to develop a mathematical model of the implementation of a “lane change” maneuver and approbation of the model on field tests.
Sidewise displacement correction movement corresponds to “lane change”. When performing this movement the wheeled mobile vehicle performs sidewise displacement and at the end of the movement restores the original sideways motion.

The form of the driver’s control action on the controls of the wheeled mobile vehicle may be different depending on the time and the way.

To model a controlled movement, it is necessary to develop elements of control actions depending on the performed maneuver.

Let us consider the execution of “lane change” maneuver, provided that the movement along a given trajectory is determined by the trajectory of the guide point, which is located in the middle of the front axle (Figure 1).

![Figure 1. Scheme of “lane change” maneuver](image)

During the maneuver, the wheeled mobile vehicle moves to the parallel trajectory passing at a distance \( H \) from the original from point \( O \) to point \( K \). The distance \( L \) characterizes the duration of the maneuver that the driver chooses, guided by external factors, for example, speed, intensity of movement, road conditions.

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The shortest trajectory required to move a mobile vehicle from point \( O \) to point \( K \) is a straight line. However, when moving along such a trajectory, it is necessary that the wheels of the mobile vehicle at point \( O \) instantly turn to the left by an angle \( \alpha = \arctg (H / L) \), and then to the right as you move along the trajectory.

Such a trajectory cannot be physically realized due to the inertia of the mobile vehicle and the human factor.

The limitations of physical realizability come down to the limitation of the spectrum function describing the control action on the steering wheel, as well as the neutralization of high-frequency control actions by the wheeled mobile vehicle.

The shortest trajectory can be represented by Fourier series:

\[
y = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi x}{L}
\]

\[
a_n = \frac{2}{L} \int_0^L y(x) \cos \frac{n\pi x}{L} \, dx = \frac{2}{L} \int_0^L Hx \cos \frac{n\pi x}{L} \, dx = \frac{2H}{\pi^2 n^2} \left[(-1)^n - 1\right]
\]
Taking into account the indicated limitation of the spectrum function, we obtain the trajectory function when performing “lane change” maneuver in the form:

\[ y = \frac{H}{2} \left(1 - \cos \frac{\pi x}{L}\right) \] (2)

The predicted motion trajectory we find the principle of steering wheels’ turn in mobile vehicle in order to ensure the realization of this trajectory.

From \( \theta \) to \( L \) the given function changes according to the principle that is close to the sinusoidal principle about the line \( y = \frac{H}{L} x \), which describes the «ideal» trajectory.

Therefore, the approximation is permissible:

\[ y = \frac{H}{L} x - A \sin \left(\frac{2\pi}{L} x\right) \]

In order to determine the unknown parameter \( A \), we use the least square method. For this purpose we solve the problem:

\[ F = \int_0^L \left( \frac{H}{2} \left(1 - \cos \frac{\pi x}{L}\right) - \frac{H}{L} x + A \sin \left(\frac{2\pi}{L} x\right) \right) x^2 \, dx \rightarrow \min A \]

Solution result is:

\[ A = \frac{H}{3\pi} \]

Thus the function approximating the “lane change” trajectory is the following:

\[ y = \frac{H}{L} x - \frac{H}{3\pi} \sin \left(\frac{2\pi}{L} x\right) \] (3)

To determine the steering wheels’ turn angle when following the predicted trajectory and when considering the low influence of the pneumatical tire drift we use the kinematic analytical scheme of the mobile vehicle wheels’ movement (Figure 2).

**Figure 2.** Analytical scheme of the mobile vehicle movement

The angle value \( \alpha \) can be found from a triangle ZOF

\[ \alpha = \arcsin \frac{B}{R} \approx \frac{B}{R} \approx BK \] (4)

where \( B \) – mobile vehicle base, m;

\( R \) – trajectory curvature radius of the front axle center point, m;
Based on the assumption, that the «change lane» maneuver is carried out with a constant speed, the motion trajectory can be described by the function of time $X \approx vt$:

$$y = \frac{H_0}{L} t - \frac{H}{3\pi} \sin\left(\frac{2\pi v}{L} t\right)$$

Trajectory curvature $K$ is described by the expression:

$$K = \frac{\dot{x}\ddot{y} - \ddot{x}\dot{y}}{\sqrt{\dot{x}^2 + \dot{y}^2}}$$

Considering the fact that, $\dot{x}^2 + \dot{y}^2 = u^2$, $\dot{x} = u_x$, $\dot{y} = u_y$, the expression for $K$ is as follows

$$K \approx \frac{\ddot{y}}{u^2}$$

Making use of the expression (5) we write

$$K = \frac{\ddot{y}}{u^2} = \frac{2\pi H}{L^2} \sin\left(\frac{2\pi v}{L} t\right) = \frac{2\pi H}{L^2} \sin\left(\frac{2\pi x}{L}\right)$$

Applying the found expression to the (4) we get

$$\alpha = \frac{2\pi HB}{L^2} \sin\left(\frac{2\pi x}{L}\right)$$

This relationship reasonably accurate describes the steering wheels’ turn process of the mobile vehicle when moving in the middle part of the maneuver. However, the beginning and the end of maneuver implementation are characterized by high values of the angular turning rates of the steering wheels.

Using the approximation $\alpha(x)$ at the initial stage of maneuver implementation under the known starting conditions for maneuver implementation, more specifically

$$\alpha(0) = 0,$$

$$\alpha'(0) = 0,$$

$$\alpha'\left(\frac{L}{4}\right) = 0,$$

$$\alpha\left(\frac{L}{4}\right) = \frac{2\pi HB}{L^2},$$

we get

$$\alpha \approx \frac{\pi HB}{L^2} \left(1 - \cos\left(\frac{4\pi}{L} x\right)\right)$$

In the same way the issue by maneuver completion is considered:

$$\alpha \approx \frac{\pi HB}{L^2} \left(\cos\left(\frac{4\pi}{L} x\right) - 1\right)$$

Therefore over the whole period of “lane change” maneuver implementation the principle of turn angle change for steering wheels is a combination of dependences.

$$\alpha = \begin{cases} \frac{\pi HB}{L^2} \left(1 - \cos\left(\frac{4\pi}{L} x\right)\right) & \text{for } x \in [0, \frac{L}{4}], \\ \frac{2\pi HB}{L^2} \sin\left(\frac{2\pi}{L} x\right) & \text{for } x \in \left[\frac{L}{4}, \frac{3L}{4}\right], \\ \frac{\pi HB}{L^2} \left(\cos\left(\frac{4\pi}{L} x\right) - 1\right) & \text{for } x \in \left[\frac{3L}{4}, L\right]. \end{cases}$$

Figure 3 shows the recommended form of control activity by the “lane change” maneuver.
Figure 3. Recommended form of control activity by the “lane change” maneuver

The analytical scheme, presented in Fig. 2, refers to the maneuver implementation method due to the steering wheels’ turn. However, if using other turn methods for example, folding the frame, the obtained dependences are also valid. In this case $\alpha$ is correspond to the folding turn of the frame.

For testing of the developed dependences, the field-control tests of the K-701c wheel-tyre tractor with a hinged frame were carried out. To determine the tractor current position coordinates the Garmin GPS navigator. The antenna of this navigator was installed on the tractor cab.

The electronic amplifier, the rotation of which was transmitted to the steering wheel by applying the toothed belt, was installed on the side panel in the tractor cab. The МУ-615А angle sensor which fixes folding the tractor frame was installed on the hinged bolt connecting the front and rear sections of the tractor.

A tractor motion control test by “lane change” maneuver implementation was carried out. A broken line composed of the rectangular fragments was taken as the predicted trajectory.

In the result of field-control tests, it was found that the control system described by these dependencies (9) is workable (Fig. 4) after the specified improvement of the electro mechanic parts. The control model can be used when carrying out field works which allow the real trajectory deviation from the predicted trajectory up to one meter.

Figure 4. Predicted and real tractor trajectory
To achieve greater driving accuracy, it is advisable to use differential corrections to improve the accuracy of determining the current coordinates of the wheeled mobile vehicle.

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