Algorithms for Controlling the Hardware and Software Platform for Moving in Virtual Reality

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Abstract. Comprehensive training of specialists in machine-building, chemical and mining industries requires the use of modern means of education. The use of software and hardware platforms based on virtual reality technologies and controlled treadmills allows for a high level of immersion in the learning process and the development of the necessary practical skills. However, the existing control algorithms for treadmills have a number of disadvantages: the effect of lag, low adaptability to human actions. The paper discusses several approaches to organizing the management of a software and hardware platform to improve the quality of movement in virtual reality. Linear and nonlinear algorithms have been developed and have been tested, and the quality of human movement in virtual reality has been made. The nonlinear modified algorithm has allowed to obtain the best results and to reduce the amplitude of oscillations relative to the initial position.

1. Introduction
In order to become a specialist in such industries as military, mining, transport, etc. [1,2], you need not only knowledge of theoretical material, but also possession of practical skills. To achieve this goal, you need to develop a comprehensive training program that will allow you to consolidate theoretical knowledge in practice and develop muscle memory.

One of the ways to solve this problem is to use systems based on virtual reality (VR) [3-6], but in this case there is no possibility to simultaneously interact with objects and move in VR. The camera is controlled with the help of controllers; because of this the user is transported (teleported) to the selected place, which, in terms of visual and physical sensations, does not correspond to the usual movement process.

The development of new systems that will separate the movement processes and VR complexes based on treadmills [7-12] for training specialists will help prevent the problem described above (Fig. 1). The advantage of this development will be to ensure realistic movement, the use of hands to interact with objects and, in general, the necessary physical training of specialists.

The laws of functioning of modern treadmills, the presence of software and hardware lags do not allow the user to comfortably move along the belt, therefore, the main task is to organize interaction with VR based on a controlled treadmill [13-16], develop new algorithms and control approaches that will increase the comfort of movement and the degree of immersion in the virtual environment.
The aim of the study is to create an algorithm for controlling the treadmill, which will promptly select the optimal speed for the treadmill, depending on the actions and speed of movement of the user, and will also allow the person to move only in the permitted ("working") area. This will also simulate the effect of movement in the real world [17].

The research examines several approaches - linear, nonlinear, modified nonlinear, their comparison and assessment of the quality of immersion in virtual reality in the complex training of specialists.

2. Algorithms for controlling the hardware and software platform

Consider in a formalized form the processes occurring when a person moves along a treadmill. The main characteristic of the treadmill user is his current position and direction of travel:

$$z_o = \frac{z}{|z|},$$

where $z_o$ is the direction of movement of a person;

$z$ is the current position of the person.

Based on the position of a person, it is possible to determine the required speed of the treadmill belt, which can be set by various algorithms:

$$speed_{lin}(z) = \frac{(|z| - z_o)\cdot speed_{max}}{1 - z_o},$$

where $speed_{lin}(z)$ is the function of calculating the speed based on a linear algorithm depending on the current position of the person $z$ and the distance from the starting $z_o$;

$speed_{max}$ is maximum treadmill speed.
The speed value obtained in formulas (2) - (4) is used to calculate the final speed of the treadmill, taking into account the location of the trainer and the current direction of his movement:

\[ V(speed) = \begin{cases} 0, & z < z_0, \\ z, & z_0 \leq z \leq 1, \\ z \cdot speed_{\text{max}}, & z > 1, \end{cases} \]

where \( V(speed) \) - a system of rules for setting the speed when a person is in various zones: safe, working and beyond its limit with a maximum speed limit.

Compare algorithms (2) - (4) in the range of changes in the position of a person \( z \) from 0.1 to 1.5. The starting point is \( z_0 = 0.1 \). It is used as the starting point. The working area of the treadmill is on the segment \([0.1; 1]\). Thus, the total length of the running platform is 1 meter of which 0.1 meters is a safe area.

The linear algorithm, increasing or decreasing the speed of the treadmill in proportion to the change in the speed of a person's movement, evenly regulates the speed along the entire length of the working area of the platform.

A nonlinear (parabolic) algorithm changes the speed of the treadmill smoothly; the speed begins to increase significantly only outside the working area (at \( z > 1 \)), which is a significant drawback: taking into account the possible software and hardware delay, such platform behavior can lead to a significant lag of the platform speed from the current human speed.

The nonlinear modified algorithm at the initial stage of movement reacts faster to changes in the position of a person on the treadmill relative to other algorithms. Thus, this behavior will reduce the lag effect, especially at the beginning of the movement when accelerating the treadmill.

Comparison of the approaches to controlling the running platform showed that the nonlinear modified algorithm provides the greatest increase in speed in the initial section of the working zone, which is characterized by the most pronounced effect of hardware lag.

Next, it is necessary to experimentally evaluate the change in the trajectory of a person when moving along the treadmill with various control algorithms.

3. Comparison of control algorithms for software and hardware platform

The developed algorithms, based on the analysis of the distance a person has moved from the starting point, increase or decrease the speed of the treadmill, but according to different laws. To determine the best algorithm, compare the trajectories of a person's movement [18]. To do this, we write down the trajectory of the change in the position of the human body without taking into account the effect of the speed of the treadmill and will use it as input data for each algorithm. Thus, the conditions for all three experiments will be identical and the results will correspond to the movement of a person with different control algorithms.

Consider the trajectory of a person's movement with a linear algorithm for controlling a running platform (Fig.2, first graph).
In Fig. 2 the trajectory of a person when moving along the track is reflected with the selected control algorithm. From the initial position (point 0), due to the lag effect, the user was able to reach the position of 0.78 m, after which he was returned to the safe zone. Further, the linear algorithm also allowed a significant deviation - up to 0.9057 m, which is close to the end of the treadmill's working area. It can be noted that due to the linearity of the control algorithm, the speed of the treadmill changes in proportion to the change in the position of the person.

With a linear approach to control, a person on average moves away from the starting point at a distance of 0.2783 m. The essence of this approach is that the speed of the treadmill changes in proportion to the position of the person. In case of a sharp change in the speed of a person due to the delay in the hardware and software of the treadmill, the algorithm does not respond quickly enough, since the person managed to move away from the starting point at a distance of 0.9057 m.

The non-linear algorithm, the behaviour of which is reflected in Fig.2 (second graph), responds to changes in the speed of a person's movement worse than the linear one. The speed increases more slowly, resulting in larger deviations from the starting point.

This approach to treadmill control realizes a smooth increase in speed at the beginning of the movement and a sharp increase towards the end of the working area. However, in practice, such smoothness led to deterioration in the trajectory of a person's movement: the deviation from the
starting point averaged 0.3589 m. The algorithm reacts to a change in the position of a person with the same dynamics as the linear one. The largest deviation from the starting point was 0.9637 m.

Consider a non-linear modified algorithm, which is based on a sharper change in speed in the initial stages of movement. The trajectory of the treadmill with this control algorithm is shown in Fig. 2 (third graph).

The non-linear modified algorithm did not allow a person to move away from the starting point at a distance more than 0.65 m. On average, a person stays at a point of 0.1691 m most of the time, which is the best result in comparison with the algorithms discussed above.

The quality assessment of the developed control algorithms is shown in Fig. 3.

![Figure 3. Comparison of algorithms by metrics.](image)

To calculate the metrics, we will use the following approach [19]: calculated the sample mean of the absolute values of the deviations of the user's position from the initial position \( (Z_A) \):

\[
Z_A = \frac{1}{N} \sum_{i=1}^{N} |Z_i|, \tag{6}
\]

where \( N \) is the total number of values in the data sample, \( n_i \) is the frequency of the value hitting the specified area. The smaller \( Z_A \), the less distance from the initial position the object was removed, i.e. the user was in one position longer, despite their own movements.

Next, we calculated the maximum deviation from the zero point \( (Z_{\text{MAX}}) \), the variance of the person's position \( (D_z) \), the standard deviation of the person's position \( (\sigma_z) \).

Dispersion \( D_z \):

\[
D_z = \frac{1}{N} \sum_{i=1}^{N} (Z_i - Z_A)^2 n_i, \tag{7}
\]

where \( Z_A \) calculated by the formula (6). Dispersion is an indicator of variation (variability) and characterizes the scatter of data in the sample, its homogeneity.

Another commonly used metric is the standard deviation \( \sigma_z \), which is the square root of the variance:
Thus, the nonlinear modified algorithm shows the best results in terms of the main metrics: the average deviation from the starting point, the maximum deviation, and has the minimum variance of the person's position.

4. Conclusion
The development of training systems based on treadmills and virtual reality complexes is an urgent task, since there are industries in which practical and physical skills play an important and sometimes crucial role. Moreover, the need to simultaneously move and interact with virtual reality objects does not allow the use of components of existing VR complexes (for example, controllers).

In the process of creating a treadmill control system, an approach was developed for collecting data on the movement of a person on a treadmill, and the collected data was processed. This made it possible to simulate the trajectory of a person's movement with linear, nonlinear (parabolic), nonlinear modified algorithms for controlling the treadmill. On the basis of experimental research and analysis of the collected data on the trajectory of a person's movement, the optimal control algorithm was selected: a nonlinear modified one, which implements a sharper change in speed in the initial stages of movement and shows the best results in terms of key metrics.

As a result of the study, it was noted that the considered approaches to treadmill control do not fully allow a person to feel confident and natural when moving. One of the ways to solve this problem is to develop a control algorithm based on neural networks [20, 21]. Therefore, a further direction of research will be the creation, training and implementation of neural networks in the control algorithms of the treadmill.

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**Acknowledgments**

This work was carried out with the financial support of the RFBR grant within the framework of the scientific project No. 19-07-00660. The work performed by the Laboratory of medical VR simulation systems for training, diagnosis and rehabilitation using the computing equipment of the Center for Collective Use "Digital Engineering".