Adaptive running training complex for the training and rehabilitation of users

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Abstract. The problems of development of the treadmill training simulator for the industrial, medical and sporting organizations are considered in the work. This simulator should provide minimum hardware-software delay for the system of automatic control. Block-diagram of the system is proposed where the main control and program blocks are allocated. Main limitations of the current hardware-software were revealed and some methods for minimization of their effects are proposed including historical data for the formation of behavioral patterns of a user.

1. Introduction
The use of treadmill training simulators as with automatic as with manual control is really actual for industry, medicine and sport. An essential drawback of the applied equipment is the delay between the readout of user’s signal and response of the control object. In the work it is proposed to implement adaptive system of automatic control with compensation of delay that is required for an adequate training and rehabilitation of the users. This will allow implementation of the control for the hardware of the training simulator in the real-time mode.

2. The features of use of treadmill training simulators
Application of the treadmill training simulators in industry is associated with practicing of the movement skills for large distances and operative evacuation. As for medicine they are applied for recovery of the muscle memory and rehabilitation after traumas of musculoskeletal system. For sportsmen they are used for the development of skills concerned with a correct respiration during walking and running of users and also for reinforcement of cardiovascular system. In each of the presented areas different modifications of treadmill training simulators are applied with the required limitations and supplements. Minimal limitations are characteristic for the sporting treadmill training simulator providing free movement of a user with a speed chosen by the user himself. Medical training simulators are characterized by enhanced safety requirements. They restrict an ease of locomotion with the use of suspension safety system or exoskeletons providing uniform load distribution while walking as well as a considerable decrease of speed for the running armored duck as compared with the sporting ones. Industry training simulators can be utilized along with the means of visual tracking such as virtual reality headsets, which can block perception of the environment by the user. The user can not even hold the handrails and the only external effect that he can perceive is a speed of the running armored duck. An important distinction
of the medical and industry training simulators is adaptation of the speed of running armored duck to the running speed of a user [1-4].

3. Algorithm of speed adaptation
Algorithm of speed adaptation for the running armored duck applied in the current training simulators is based on the deviations of user’s coordinates from the reference point of the running armored duck. These coordinates of a user are calculated relative to the fixed point arranged, for example, at the safety rope while zero reference point of the running armored duck is a spatial tag arranged at a certain distance from the stationary object, for example, rail or back wall of the training simulator. Deviation of the user from zero reference point is calculated by a system of the information processing and then it is transferred to the automatic control system (ACS) in order to form the response of the running armored duck. The value of response is modulo equal to the speed of user but is opposite in direction.

Similar approaches to obtain control action of ACS are feasible for the uniform walking of the user when the speeds of walking for the long periods of time remains either invariable or its changes are rather slow. In these cases running armored duck also moves with the minimal changes in speed. This approach is used for rehabilitation when the user can move with a permanent speed holding by the handrails.

ACS of the industry treadmill training simulators using such kind of the control for speed responses to the changes of the user’s speed with a considerable delay thus preventing full-fledged flooding into virtual reality [5, 6].

4. Classical approach to the control for treadmill training simulators
Consider classical scheme of operation of the treadmill training simulator with the system of automatic control (figure 1). Vertical axis represents speed (m/s), horizontal axis shows time (s), blue curve is speed of a user, \( V_U(t) \), while orange curve is a speed of armored duck \( V_B(t) \).

![Figure 1](image)

**Figure 1.** Plot of operation of the treadmill training platform with a delay of response.

Three main fragments can be distinguished in figure 1:
1) acceleration of the user and running armored duck from the moment of stop up to the constant speed (labeled with a green frame):

\[
\begin{cases}
V_U(t) > V_B(t) \\
V_U'(t) > 0
\end{cases}
\]  
(1)

2) movement of the user with a constant, convenient for a user speed, and the speed of the running armored duck is equal to the speed of user (labeled with a blue frame):

\[
\begin{cases}
V_U(t) = V_B(t) \\
V_U'(t) \approx 0
\end{cases}
\]  
(2)
3) deceleration of the user up to a stop (снижение скорости пользователя до остановки) (labeled with a red frame):

\[
\begin{align*}
V_U(t) &< V_B(t), \\
V_U'(t) &< 0
\end{align*}
\]

\(3\)

Distance between the plots of \(V_U(t)\) and \(V_B(t)\) is just a firmware delay (\(\tau\)) of ACS under the change of the user’s speed: at the horizontal part of the plot the graphs practically coincide (\(V_U'(t) \approx 0\)); in the areas where \(V_U'(t) \neq 0\) the distance between them along the time axis equals \(\tau\).

If the delay \(\tau\) is quite considerable the use of such training simulator seems to be practically impossible by the reason of inadequate sudden changes of running armored duck speed which have the effect on the proprioceptive sensations and vestibular apparatus of the user. If blocking of the environment perception by the user takes place his vestibular apparatus cannot adequately perceive the unnaturally changing speed of the running armored duck and so the user will be focused not on the task accomplishment but rather on keeping his equilibrium [5-8].

To solve the problem of delay in ACS response preventing the natural movement of the user the development of the system for adaptive prediction of the user’s position is required relative to the running armored duck [3,4].

5. Problem formulation
The goal of the study is a minimization of the firmware delay in the system of automatic control:

\[
\tau \rightarrow \min
\]

\(4\)

To attain this goal prediction of the user’s position after specified time interval \(\theta \geq \tau\) is used. For the prediction of the user’s speed \(V_U(\theta)\) historical data (templates) are used concerning the models of his behavior:

\[
\bigcup_{t=0}^{\tau} V_U(t) \rightarrow V_U(0) \mid \theta > \tau
\]

\(5\)

6. Prototype
The proposed block diagram of the prototype of running armored duck is presented in figure 2.

![Figure 2. Block diagram of the treadmill armored duck platform.](image)

Treadmill armored duck platform (TDP) is divided into the following systems consisting from the firmware blocks, and their development and modernization was implemented in accordance with the limitations of their application [9]:

CP – system joining several control panel that accomplish the control for operation of TDP and the change of the functioning mode with the account limitations;
SPI – is a system for the information processing meant for the accomplishment of acquisition, processing and synchronization of the information concerning the commands received from CP and automated SPI blocks. SPI implements control for the order of commands execution by the execution components as well as duplicates these commands to all of CP;

SPP – system of the process for preparation, which realizes storage and connection of the models for the control of TDP, connection of the models for visual tracking as well as for the patterns of the user’s actions;

SVP – system of visual positioning, which accomplishes data processing obtained from positioning cameras (streaming processing of video streaming in order to reduce the load for SCM);

SCM – is a system for calculation of motion of the user relative to reference zero point of the treadmill armored duck of training simulator. System chooses the pattern of maximum realistic movement of the user over the operation area of TDP with the account of the system inertia. It also defines the control of the current position and thus provides control action with the account of restrictions received from the control panels and safety requirements;

OA – operation area of the treadmill armored duck platform supplemented with the units for the control of the changes in positions of the executive elements which determines the value of the control actions on the power unit of TDP. Calculations of the changes in position are done with the account of the system’s limitations and safety requirements in the use of equipment.

According to the presented structure scheme information about the user is received from SVP and further is analyzed and the control action on the TDP forms OA. The represented structure elements are firmware components the change of parameters in each of them provides the corresponding delay, therefore delay of the system is:

\[ \tau = \sum_{i=1}^{6} \tau_i \]  

where \( i \) – is a number of structure component (1 – CP, 2 – SPI, 3 – SPP, 4 – SVP, 5 – SCM, 6 – OA). Numerical value of \( \tau_i \) is an individual one for each of the firmware package, so in order to perform calculations it is required to use data obtained experimentally.

While executing the investigations a prototype of TDP (figure 3) was created according to the presented structure scheme. This prototype is an analogue of the treadmill training simulator applied in industry.

With its aid it was experimentally proved the presence of the firmware delay \( \tau \) even at the minimal calculation processes. The most serious effect on the value of \( \tau \) is exerted by the action of executive elements. This is connected with the changes of the instant speed of the users: in the beginning of walking after the stop the reference control point of the user gains a great acceleration that is transferred to ACS; then ACS transfers the value of acceleration to the executive element which cannot instantly provide the desired speed to the treadmill armored duck. While ACS increases acceleration of the treadmill armored duck the user attains permanent speed. During the period when the user moves with a permanent speed ACS varies the acceleration. The moment of the change in acceleration is sensed by the vestibular apparatus of a user. This makes him to concentrate on keeping the equilibrium and to decelerate or even to stop. Treadmill armored duck returns the user by inertia back to the zero reference point and ACS transmits stop signal to the executive elements. The user perceives the stop, vestibular apparatus is soothed and the user once again starts moving.
7. Investigations
Experimental investigations demonstrated that:
- the use of tag applied as the reference point arranged at the user’s belt does not allow constructing of not only forecast [10, 11], but also the patterns of actions providing a precise classification of behavior;
- at the large weight of a user the friction force arising on the drive shafts is less than the friction force arising at the operation area, i.e. the starting shaft torque should be adapted not only basing on the construction of simulator but also basing on the user’s weight;
- movement of the user at the low speed promotes the appearance of the slip between the components of «driving shaft-treadmill armored duck». This provides periodic pulses perceived by the user as proprioceptive ones thus preventing not only preparation and rehabilitation but also to the analysis of the user’s state;
- in order to form the patterns of the user’s behavior it is insufficient to use coordinates of only one point arranged at the safety belt.

8. Future investigations
In order to form the patterns of the user’s behavior it seems rather perspective to use the suite of the motion capture for the virtual reality (figure 4). This suite comprises a set of sensors for the determination of spatial coordinates in three planes, and it also automatically acquires data on the accelerations and the changes of slope angles for the control points.

The control points of the suite represent sensors arranged on the belts firmly fixed on the user. Sensors make it possible to form skeleton of a user (figure 5), for the following formation of the behavior patterns. Points A-N represent the control segmental parts of surface at the suite for the capture of motion. The edges connecting points prove to be the bones of use’s skeleton. In order to arrange the bones and specify the dependences between the control points the use of neural networks is justified as for the following formation and classification of the patterns for the user’s behavior.
9. Conclusion

Development of the system for automatic control of the treadmill armored duck platform is a complex process requiring a lot of investigations of human-machine systems, as well as accounting of not only an accuracy of accomplishment of the automation actions, but the individual activity of different users. While interactions with the treadmill armored ducks platforms, when the user directly effects on the system while the system indirectly influences on the user, it is required to account not only the effect and responses at the instant moment of time, but also the firmware delay of the components as well as influence of inertial forces and the freedom of the user’s actions (disturbing impacts, clutters). The use of historical data on the movement of the user over treadmill armored duck allows classifying the model of the user’s behavior, to consider its dynamics and even to construct a forecast. To increase accuracy of the forecast it is necessary to account not only for the movement of the safety belt (center of mass) of the user but also the dynamics of the motion of his extremities.

Acknowledgements

Investigations were executed under financial support of RFBR within the frames of scientific project: contract № 20-37-90041/20 on 20.08.2020

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