Application of active exoskeletons with touch sensing, electric drives, energy recuperators and gravity compensators in agricultural technologies

A V Borisov¹⁺, V I Borisova², L V Konchina¹, M G Kulikova¹ and K S Maslova¹

¹ Branch of the "national research UNIVERSITY "MPEI" in Smolensk, Energeticheskiy proezd, house 1, Smolensk 214013, Russia
² Federal State Budgetary Educational Institution of Higher Education "Smolensk State Agricultural Academy (FGBOU VO Smolensk State Agricultural Academy), Bolshaya Sovetskaya street, house 10/2, Smolensk 214000, Russia

* E-mail: borisowandrej@yandex.ru

Abstract. The article describes a model of a digital human-machine system, in the form of a three-dimensional model of an active exoskeleton with five links of variable length, developed for possible use in agriculture. The difference between the proposed model of an active exoskeleton and the existing ones is that links are used that can change their length under the action of applied loads, and energy recuperators are built into these links. In each joint of the links between each other there are gravity compensators. These design solutions can reduce the load on the electric drives of the exoskeleton and increase the battery life of the device, which is important when used in agriculture. As an interface between a person and an exoskeleton, touch sensing will be used. The principle of operation is that the signals from the touch sensors will be sent to the control module of the exoskeleton, amplified and implemented by electric drives in accordance with the movement of each link of the human endoskeleton with minimal delay. Each link of the exoskeleton consists of two sections of constant length, having a mass, and one weightless section between them, changing its length. The links are connected to each other by a combination of joints. A set of differential equations is written in the form of a system describing the exoskeleton dynamics. This system was written in a generalizing matrix-vector form. Much attention is paid to the possibility of real application of the proposed model of the active exoskeleton in agriculture and the positive results arising from its practical use.

1. Introduction
Creating a comfortable and safe working environment for agricultural workers with the help of high-tech active exoskeletons that form a single digital human-machine system will increase the prestige of rural labor and help to reduce the outflow of young people to large cities. The active exoskeleton has not only an important socio-economic value, allowing to increase the strength and endurance of the user to increase labor productivity, but also medical one - allowing to reduce occupational diseases, reduce injuries of rural workers. Therefore, the use of exoskeletons is possible not only in industry, rehabilitation and gerontological centers of Russia, as evidenced by a large number of publications [1-5], but also in agriculture [6-8]. At the same time, the existing designs are very simplified and are not full-fledged robotic devices. Accordingly, modeling the movements and interaction of digital human-machine systems in the form of multi-link spatial anthropomorphic mechanisms with such links that
can change the distance between the axes of rotation in the hinges, taking into account elastic elements - energy recuperators, gravitational compensators, sensors, control system and electric motors to change the relative position of the links; possible controlled transformation of the distance between the axes of rotation in the joints connecting the links, is a significant task that has a maximum of practical agricultural applications, which determines the topicality of the research topic. The significance lies in the creation of the latest class of agricultural auxiliary robotic devices of anthropoid structure, which increase the strength and endurance of a person due to the external frame. Thus, the creation of active exoskeletons in the form of mechanical mechatronic digital human-machine systems can become a point of growth and development of breakthrough technologies of scientific and socio-economic development of Russia.

2. Materials and methods
The model of the active exoskeleton consists of such links that allow to change the distance between the axes of rotation in the joints (Fig. 1), connected by a combination of two cylindrical joints that provide the necessary mobility of the links connection for anthropomorphic movement.

The link that allows to change the distance between the axes of rotation in the joints includes a massless part that can change its length, and two solid inertial parts with lengths $l_{ij}$ ($i = 1, 2, \ldots, 5$ – the number of composite links; $j = 1, 2$ – the numbers of solid sections having mass), which can make a relative movement along the segment passing through the end and beginning of the composite link. That is, the change in the distance between the axes of joints rotation is realized due to the movement of inertial solid sections on a segment of variable length $B_{i}C_{i} = \xi_{i}(t)$ ($i = 1, 2, \ldots, 5$). Thus, the link as a whole has variable inertial characteristics in the process of movement. Between the solid inertial sections inside the link, a spring element is installed, which is an energy recuperator, in the form of a tension-compression spring. Electric motors with rack and pinion or helical transmission are also installed, which implement a controlled change in the distance between the axes of rotation in the joints, i.e. the length of the link. Each subsequent link is connected to the previous one by a combination of two cylindrical joints that are mutually perpendicular to each other and provide the necessary mobility of the links. A gravity compensator in the form of a torsion spring is installed in the joints. In the area of articulated connections, electric motors with reducers are installed, providing controlled rotational relative movement of the links. The lower leg of the support leg, which is the first link, is connected by a weightless foot $O_{1}A_{0}$ with a fixed support. The lower leg of the shifted leg is connected to the weightless foot $O_{2}A_{4}$. It is assumed that the friction force that occurs in the contact zone of the exoskeleton foot with the support is sufficient for the absence of slippage when walking.

The position of the mechanism is determined uniquely by the angles that form links between each other $\varphi_{i}(t)$, $\psi_{i}(t)$ and variable distances between the axes of rotation in the joints, which are obtained due to the use of links sections $\xi_{i}(t)$ ($i = 1, 2, \ldots, 5$). The considered 3D model of the exoskeleton for agricultural workers has fifteen degrees of freedom.

Masses of inertial solid parts of links $A_{i}B_{i}$ have values $m_{1i}$, characteristics that have their meaning as the inertial properties of a body during rotational motion about an axis passing through the point where its mass is concentrated perpendicular to the plane in which the motion occurs, $I_{1i}$. The inertial characteristics of the translational motion of the sections $C_{i}A_{i+1}$ are equal to $m_{2i}$. The moments of inertia of the links sections about the axis that passes through its end orthogonally to the plane of motion, $I_{2i}$. Density of the $j$-th weighty section of the $i$-th link, $\rho_{ij}$ ($i = 1, 2, \ldots, 5; j = 1, 2$).
Figure 1. Spatial model of the exoskeleton with five links of variable length.

The energy of motion of the links is the sum of the kinetic energies of the solid inertial sections of the links $A_i B_i$ and $C_i A_i$. They perform a complex movement: progressive along the link direction and rotational near the pole located in the joint, with which it is attached to the previous link. The equations of the exoskeleton motion in a generalized matrix-vector form, which are differential, have the form:

$$
D_\kappa(\phi,\psi,\xi) \dot{\Phi} \phi + A_\kappa(\phi,\psi,\xi) \phi + C_\kappa(\phi,\psi,\xi) \ddot{x}_\kappa + 
E_\kappa(\phi,\psi,\xi) \dot{\Psi} \psi + B_\kappa(\phi,\psi,\xi) \psi + 2F_\kappa(\phi,\psi,\xi) \ddot{\xi}_\kappa + 
gK_\kappa(\psi) + 2H_\kappa(\phi,\psi,\xi) \dot{\xi}_\kappa + 2G_\kappa(\phi,\psi,\xi) \dot{\xi}_\kappa \dot{\psi}_\kappa = M_\kappa(\phi,\psi,\xi),
$$

(1)

The indices located near the matrices at the bottom indicate the description of the generalized coordinate: $\kappa = 1, \ldots, 3$, where 1 corresponds to the generalized coordinate $\phi$, 2 $\psi$, 3 $\xi$; column vectors $\phi = (\phi_1, \ldots, \phi_n)^T$, $\psi = (\psi_1, \ldots, \psi_n)^T$ – angle vectors; $\xi = (\xi_1, \ldots, \xi_n)^T$ – vector containing information about sections of variable length of links; $\Phi = \text{diag}(\phi_1, \ldots, \phi_n)$ – diagonal matrix; $\dot{\phi}$ – angular velocity vector; $\dot{\phi}$ – angular acceleration vector; $M$ – vectors specifying control actions in the form of moments [N-m] and forces [N] on the sections of the links that change their length; $A, B, G, H$ – matrices that allow to consider the properties of the inertial system; $C, K$ – matrices determined by the moments of gravity; $D, E, F$ – matrices considering changes in the length of the links.
The input effects are the movements of the human endoskeleton links and muscle electrical impulses recorded by touch sensors. Further, the electrical impulses taken with the help of a myogram are converted into control signals for electric drives located in the joints into control actions.

The output signals are the movements of the exoskeleton links, scaled and synchronized with the movement of the corresponding links of the human endoskeleton.

**Assembly units and parts of the active exoskeleton model.**

Exoskeleton designs provide for the use of a wide range of assembly units, the main ones of which are presented below, which ensures the versatility of the structures and allows to expand the functionality and applications.

1. Cylindrical joints with torsion springs in the form of a combination of two joints in mutually perpendicular planes.
2. Variable length links with compression springs and two rods.
3. External load-bearing rods for links with a cylindrical cross-section profile.
4. The inner rods are thin for sections with compression spring and solid cross-section profile.
5. Compression springs of different stiffness for different parts of the leg.
6. Bearings for cylindrical joints.
7. Torsion springs of different stiffness for different parts of the leg.
8. Fasteners connecting bearings, electric motors, rods and springs.
9. Fabric fasteners of the exoskeleton and sensors to the links of the human endoskeleton on retainers.
10. Corset.
11. Protective covers for bearings and torsion springs.
12. Protective covers for compression springs.
13. Sensors with ADC.
14. Control computer.
15. Electric drives.
16. Wires, fasteners, other devices.

**Description of the model functioning**

The exoskeleton model is an electromechanical structure described above with detectors in the form of sensors and motors that operate using electricity. Actions are based on the fact that with the help of the exoskeleton, the movements of the links of the human endoskeleton are directed, amplified and implemented. The mechanism of energy recovery lies in the fact that the energy of movement, which is accumulated in the springs when the foot is placed on the support, is returned when the foot is pushed away from the support and the spring is released. This way, it will be easier for the user to complete the step. Therefore, part of the load will be removed from the muscles of the human endoskeleton and the battery charge will be saved. Similarly, gravity compensators in the form of torsion springs will compensate for part of the load during flexion-extension in the joints. Thus, a model of the exoskeleton with energy recuperators, gravity compensators, sensors and electric drives will be created.

The battery is attached in the area of the hip joint - point $A_2$ and rests on the links that form the legs. The choice of such a place for fixing the battery is justified by the fact that it is a fairly massive part of the exoskeleton and, in order to reduce the impact of this additional mass on the dynamics of the human-machine system, it is attached as close as possible, but below the total center of mass of the system.

Based on the information received from the touch sensors attached to the human, a control method based on empirical information developed in works [9-11] is implemented. At the same time, due to the presence of a control unit, the exoskeleton can correct the user's movements using control methods based on the results obtained in the framework of theoretical mechanics models [12-14].

At rest, the user is inside the human-machine system in the form of an active exoskeleton. The load from the upper part of the human endoskeleton, i.e. the body and arms, is distributed to the upper part of the exoskeleton $A_2A_5$ (Fig. 1). The load from the lower part of the human endoskeleton, i.e. the legs,
is distributed to the retainers for the hip and legs $A_2$ (Fig. 1) and rods that allow to change the distance between the axes of rotation in the joints for the hip $A_1A_2$ and $A_3A_2$ (Fig. 1), the lower leg $A_4A_2$ and $A_5A_2$ (Fig. 1) and the weightless feet $O_7A_6$ and $O_8A_4$, attached at points $A_6$ and $A_4$ (Fig. 1). Maintaining the pose is realized due to gravitational compensators in the form of spiral springs, which are installed in the joints and are in the equilibrium position in the deformed state. Compression springs on sections of links that change their length are loaded slightly and partially compressed.

In dynamics, electric drives implement amplified signals coming from the control unit based on information received from sensors, and spring elements reduce the load on all parts of the endo- and exoskeleton.

**Numerical characteristics of the model.**

To make it possible to compare the results obtained in previous works on exoskeletons, we use the values of parameters for numerical calculations for the average person, similar to our works [9-11]. We assume that the mass of the exoskeleton link is 30% of the mass of the corresponding link of the human endoskeleton. Initial lengths of links that were not deformed: $l_1^* = l_4^* = 0.385$ m, $l_2^* = l_5^* = 0.477$ m, $l_3^* = 0.771$ m. They were divided as follows on the link: $l_{11} = l_{41} = 0.15$ m, $l_{21} = l_{31} = 0.085$ m, $l_{22} = l_{32} = l_{42} = l_{52} = 0.2$ m, $l_{23}^* = l_{33}^* = 0.077$ m, $l_{34} = 0.3$ m, $l_{44}^* = 0.171$ m, $l_{31} = l_{52} (i = 1, \ldots, 5)$. Link weights $m_1 = m_2 = 2.91$ kg, $m_3 = m_4 = 8.93$ kg, $m_5 = 28.93$ kg. These masses were divided into two between two inertial solid sections of the links: $m_{11} = m_{12} = m_{1}/2 (i = 1, \ldots, 5)$. The moments of inertia of the weighty sections of the links relative to the axis that passes through the lower point of the weighty part of the link have the following values: $I_{11} = I_{11} = 0.011$ kg·m², $I_{21} = I_{31} = 0.060$ kg·m², $I_{34} = 0.434$ kg·m², $I_{31} = I_{52} (i = 1, \ldots, 5)$. The time of the single-support phase $t_s = 0.36$ s. [9-11]. The characteristic showing how quickly the velocity changes when a body moves vertically downwards freely near the Earth’s surface in the absence of drag forces: $g = 9.81$ m/s².

**3. Results and Discussion**

As a result of theoretical calculations of the parameters of a passive exoskeleton for an adult, it is obtained that the stiffness of spiral springs located near cylindrical joints should be from 2000 Nm. The stiffness of the springs in a straight line links: from 1000 N/m. The effect of energy recovery is expected to be 25%.

The maximum impulse load values that electric drives should implement are as follows: for joints installed in the ankle joint up to 8000 N·m, which develop at the moment of repulsion. These loads are significant and are considered in the requirements when choosing an electric motor and gearbox. For compression springs, the maximum value is 500 N, which can be realized by means of an electric motor and a rack and pinion or screw drive.

The active exoskeleton is designed to unload the human endoskeleton and help it when walking and performing labor operations. The device will soften the shocks that occur when the foot is placed on the support surface, due to energy recovery, and help with pushing the support leg away from the surface.

Thus, an active exoskeleton with touch sensitivity, electric drives, energy recuperators and gravitational compensators has been developed, which, due to energy recovery, electric drives and load redistribution, provides the possibility of reducing it on the elements of the human endoskeleton, protecting it from injuries, increasing the strength and endurance of the agricultural worker.

**4. Conclusion**

Exoskeletons are devices highly effective in technological, consumer, medical, rehabilitation and economic terms. Exoskeletons are able to combine several useful properties in one device at the same time. For example, strengthening the physical capabilities of a person, increasing endurance, duration of working time in it, protection from injuries, occupational diseases.

However, currently the market is experiencing a clear shortage in the developed products. Available models of exoskeletons have piece sales and high price. Some models are not sold at all, but only rented out. This allows for the establishment of mass production of comfortable models of active
exoskeletons to hope for a reduction in prices and obtaining a significant share of the still practically free market. On the Hype cycle, exoskeletons are currently marked as a technology heading for the "peak of inflated expectations". At this point in time, there are models of exoskeletons on the market only for the lower extremities.

From a brief review [1-11] and regular monitoring of this topic, it follows that no company has yet established mass production of exoskeletons at affordable prices. The industry is at inception and development stage, although there is more work to be done. In the electronic library of the RSCI citation system, the number of publications on the topic of exoskeletons over the past ten years has increased from 36 in 2010 to 433 in 2019, published patents from 0 in 2010 and 1 in 2011 to 39 in 2019. The prospects for the development of the industry are very large, as well as the possibility of using active exoskeletons in industrial and agricultural technologies.

Acknowledgements
The reported study was funded by RFBR and Smolensk region, project number 19-48-670002

References
[1] Piña-Martínez E and Rodriguez-Leal E 2015 Mathematical Problems in Engineering 145734 p 14
[2] Bortole M, A. del Ama, Rocon E, Moreno J C, Brunetti F and Pons J L 2013 A robotic exoskeleton for overground gait rehabilitation Proceedings of the IEEE International Conference on Robotics and Automation (ICRA '13) pp 3356-3361
[3] Hassan M, Kadone H, Suzuki K and Sankai Y 2012 Exoskeleton robot control based on cane and body joint synergies Proceedings of the 25th IEEE/RSJ International Conference on Robotics and Intelligent Systems (IROS '12) pp 1609-1614
[4] Tsukahara A, Hasegawa Y, Eguchi K and Sankai Y 2015 IEEE Transactions on Neural Systems and Rehabilitation Engineering 2 pp 308-318
[5] Tsukahara A, Hasegawa Y and Sankai Y 2011 Gait support for complete spinal cord injury patient by synchronized leg-swing with HAL Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS '11) pp 1737-1742
[6] Toyama Shigeki & Yamamoto Gohei 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2009).pp 5801 - 5806
[7] University of Saskatchewan, https://research-groups.usask.ca/
[8] Robohub, https://robohub.org/
[9] Borisov A V and Rozenblat G M 2017 Journal of Applied Mathematics and Mechanics 81 pp 351-359
[10] Borisov A V and Rozenblat G M 2018 Journal of Computer and Systems Sciences International 2 pp 319-347
[11] Borisov A V 2019 Two-dimensional and three-dimensional models of anthropomorphic robot and exoskeleton with links of variable length Proc. of 24th Int. Conf. “MECHANIKA 2019” pp 26-39
[12] Mukharlyamov R G, Tleubergenov M I 2017 Distributed Computer and Communication Networks. DCCN 2017. Communications in Computer and Information Science 700 pp 431-442
[13] Kaspriovich I E 2016 Application of Constraint Stabilization to Nonholonomic mechanics 2nd International Conference on Industrial Engineering, Applications and Manufacturing (ICIEAM)
[14] Golubev Yu, Melkumova E 2018 Two-legged Walking Robot Prescribed Motion on a Rough Cylinder AIP Conference Proceedings 1959 030009