INTRODUCTION

The study of the potential capabilities of autonomous robotic walkers to overcome obstacles is of theoretical and practical interest [1, 2]. The line of development [3–5] of specialized contrivances for legs is fairly simple from an algorithmic standpoint, but certain properties of the support surface that are somewhat hard to reproduce in real life are implied here. The development of movement algorithms for an insectomorphic robot that is to overcome complex high obstacles relying only on Coulomb friction forces was discussed in [6–10].

The problem of the robot’s displacement using balls may arise, for example, when a ball resting on a support obstructs the movement of this robot in the needed direction, and all possible ways to maneuver around the ball do not satisfy the passability conditions. This problem may also arise when a ball resting on a support needs to be repositioned, and the robot is not capable of lifting this ball. The problem of a robot moving from a shelf to a massive ball that may roll along a horizontal plane, the subsequent longitudinal acceleration and deceleration of the ball achieved by making the robot perform certain special movements on the ball, and the robot moving from the ball to another shelf was analyzed constructively in [11]. A way to solve the problem of a robot climbing from a horizontal plane onto a freely moving ball was described in [12]. A solution to the problem of the robot moving from one ball that is initially at rest over to another such ball that always stays in contact with the first one was presented in [13]. An algorithm for a robot climbing over a freely rolling ball (one of the possible ways to overcome such an obstacle) was derived in [14].

The present study serves as a continuation of [11–14] and is focused on investigating the possibility of altering the direction of velocity of the ball’s center by shifting the center of mass of a robot from the vertical line that goes through the ball center. It is demonstrated that such maneuvering is possible, but inevitably produces a certain spin of the ball about the vertical, thus complicating considerably the execution of the required movements of the legs and body relative to the reference points. Such a spin is hard to measure and predict, and a system of a freely rolling ball and a robot on top of it is highly unstable. At the same time, a certain shift of the center of mass of a robot from the longitudinal vertical plane is always produced as this robot moves along the surface of a ball (for example, due to the errors in execution of the required movements). The influence of this specific feature on the control algorithm is manifested clearly in the following locomotion problem. Two identical movable balls located at a certain distance from each other
and an insectomorphic robot are at rest on a horizontal plane. The robot must approach one of the balls, climb on top of it, roll this ball close to the other one, and get down to the horizontal plane. A certain vertical spin of the ball with the robot is produced as this ball gets closer to the other one. Since the balls should come in contact with each other, a collision occurs, and the spin is transferred to the second ball. If the first ball is rolled close to the second one carelessly, the disturbance in the movement of balls after the collision does not allow one to solve the stated problem. A constructive algorithm for solving the formulated problem is presented below. This algorithm was worked out using the Universal Mechanism software package [15] with the complete dynamics of the system as a whole taken into account. The results of computer modeling suggest that the proposed algorithm is implementable.

1. ROTATION OF THE BALL VELOCITY VECTOR

It is assumed that a ball with radius $R$ and mass $M$ may roll along a horizontal plane without slippage and bouncing. The center of mass of a robot is located at a distance $h > 0$ from the ball surface. Let us analyze the movement during which the robot body shifts from the vertical, which goes through the point of contact between the ball and the plane, in such a way that the radius vector $r_m$ of the center of mass of the robot drawn from center $B$ of the ball always remains perpendicular to velocity vector $v \neq 0$ of the ball center and makes angle $\psi$ with the mentioned vertical. In this case,

$$r_m = (h + R)\left(\mathbf{e}_z \cos \psi + \frac{\mathbf{e} \times v}{v} \sin \psi\right),$$

where $\mathbf{e}_z$ is a unit vector of the vertical and $v \neq 0$ is the magnitude of velocity of the ball’s center. Let us neglect the variation of the total angular momentum of the legs relative to the center of mass of the robot and assume that the robot is, on the average, moving in parallel to the plane that is perpendicular to the velocity vector and goes through the ball center. The absolute angular velocity $\omega_r$ of the robot and the absolute velocity $v_r$ of its center of mass are then expressed in the following way:

$$\omega_r = \frac{\dot{\psi}}{v} v + \frac{R \omega_p}{\rho} \mathbf{e}_z, \quad v_r = \dot{\psi}(h + R)\left(\frac{\mathbf{e} \times v}{v} \cos \psi - \mathbf{e}_z \sin \psi\right) + v,$$

where $\omega_p$ is the horizontal component of the angular velocity of the rolling ball and $\rho$ is the radius of curvature of the trajectory of the ball center. Let us denote the point where the ball touches the supporting plane as $A$ and use the theorem of variation of angular momentum $K_A$ (of the ball together with the robot) with respect to generally moving point $A$ [16]:

$$\frac{dK_A}{dt} + v_A \times Q = r_m \times mg,$$

where $t$ is time, $v_A$ is the velocity of point $A$, $Q$ is the linear momentum of the system, $m$ is the robot mass, and $g = -ge_z$ is the gravitational acceleration vector. The expression in the right part for the gravitational moment of the robot with respect to point $A$ holds true due to the fact that radius $BA$ is always parallel to the gravitational force.

Let us assume that the mass distribution within the ball is centrally symmetric with respect to point $B$. The angular momentum $K_B$ of the ball with respect to point $A$ then takes on the following form:

$$K_B = J_b \omega,$$

where $\omega$ is the angular velocity of the rolling ball and $J_b$ is the moment of inertia of the ball with respect to the axis that goes through $A$. In a homogeneous ball, $J_b = 7MR^2/5$. Let us assume that the direction of velocity of the ball center corresponds to the principal axis of inertia of the robot in the middle position of its legs with respect to the body. The angular momentum $K_r$ of the robot with respect to the same point is then written as [16]

$$K_r = -\frac{J_b \psi}{v} v + \frac{J_b R \omega_p}{\rho} \mathbf{e}_z + m(Re_z + r_m) \times v_r,$$