Design of the Walking Pattern Generation Software of AR-600 Anthropomorphic Platform

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Abstract. Biped walking implies a multitude of cyclically moving body segments and requires corresponding adjustment and coordinated movement of these segments to ensure smooth motion and balance maintenance – a challenging task considering technical limitations of currently existing robotic platforms. The article describes the implementation of the real-time dynamic walking of the AR-600 anthropomorphic robotic platform produced by JSC NPO Androidnaya Tekhnika (Magnitogorsk, Russia). The robot was controlled employing the software developed by the authors and motions were simulated in the 3DLK specialized simulation environment (JSC NPO Androidnaya Tekhnika). The authors studied various walking trajectories and confirmed the validity of this algorithm and related software for implementing biped robot locomotion.

1. Introduction
Locomotion is the ability of animals and humans to move from one place to another. Humans demonstrate very reliable, universal and energy-efficient functional capacities within a wide range of locomotion conditions. Achieving equally stable and efficient walking is one of the most important challenges in anthropomorphic robotics. However, transferring the principles of human motion into robotized platforms is a complicated task due to the limited capacities of the currently available technological solutions and the absence of the full understanding of interactions between the sensory-motor mechanisms that take part in human walking [1].

The primary difficulty with biped walking implementation is maintaining motion balance: there are two types of robot walking that solve this problem differently, i.e. static and dynamic walking. Static walking implies that the robot’s position is stable at any moment. As opposed to static walking, dynamic walking is characterized by the moments of a robot’s motion when the mass center projection leaves the support polygon, which means an inevitable fall for the body. It is prevented by the creation of new support. Dynamic walking ensures the higher stability of robot’s movements and allows realizing a wide range of locomotion speeds. The implementation of biped robot locomotion can be relatively divided into the following stages: planning a desirable motion trajectory, determining a motion trajectory for the robot’s center of mass and its extremities while maintaining balance and natural walking, solving the task of inverse kinematics to determine angle values for robot joints and transferring data about corresponding changes in these values to robot motors.

One of the main challenges in real-time walking implementation is a need to establish continuous control over the robot and its motions and simultaneously accomplish such tasks as environment
recognition and trajectory planning mission with due account for the limited technical and computational capabilities of the used hardware.

2. Literature review

Human walking is performed in a vertical position by means of two legs: a walking cycle can be divided into two main phases, i.e. the stance phase when the foot is in contact with the ground, and the transfer phase during which the foot is in the air. Each of these phases has its own functional goal. The stance phase ensures the forward movement of the body and vertical posture maintenance, while the transfer phase is needed to move the leg and prepare for the next step. This process can be more simply described with a model of an inverted pendulum formed by the body center of mass and the stance leg. This model and its variations [2–4] are the most common approach to simulate the robot’s center of mass.

The following methods are used to assess the dynamic stability of the robot: centroidal angular momentum, footstep-based criteria, periodicity-based gait and zero moment point [5]. The zero moment point (ZMP) method is the most popular option. The zero moment point concept specifies a point with respect to which dynamic reaction force does not produce any moment in the horizontal direction during contact between the foot and the ground, i.e. a point where the sum of horizontal inertia and gravity forces equals zero [6]. Therefore, the zero moment point characterizes the dynamic stability of the robot and is frequently used as a criterion to assess motion stability.

Kajita et al. [7] proposed an algorithm for preview control over the zero moment point. The algorithm suggests using the zero moment point as an entry parameter that determines a motion trajectory for the robot’s center of mass, and the problem of its timely variation is solved by means of preview control [8]. This method allows setting precise feet coordinates, which is a benefit when anthropomorphic robots are used to performed specific actions, such as moving in narrow passages, transferring objects in residential facilities, etc. Its relative simplicity of implementation and low cost of calculation allow using this method to organize real-time control over robots.

3. Proposed methodology

The motion algorithm based on preview control was realized as a separate software library integrated into the control software developed by the authors for the AR-600 anthropomorphic robotic platform. The software elements were written in the C++ language in the Qt Creator 4.8.2 programming environment. No third-party solutions or libraries were used. The algorithm was tested on a personal computer with the following features: Intel Core i5-4440 CPU 3.10 GHz, 8 GB RAM.

These solutions were tested and debugged via the specialized 3DLK simulation environment (NPO Androindaya Tekhnika). This environment allows assessing the operational integrity of the solutions without using an expensive robotic system exemplar (figure 1).

The AR-600 anthropomorphic robot model used in these tests has the following parameters: dimensions – 496 x 260 x 1,442 mm, weight – 65 kg, overall number of the degrees of freedom – 59, 12 of which fall at the lower extremities. The robot utilizes commutator DC motors. The robot is equipped with the following sensors: magnetic encoder – 21 pcs (12 bit), incremental optical encoder – 21 pcs, six-axis gyroscope-accelerometer ADIS 16400 – 8 pcs, IR distance sensor – 2 pcs, foot pressure sensor – 8 pcs. The robot utilizes the Avalue QM-57 onboard computer.
4. Algorithm
Overall, the implementation of the robot’s motion implies determining the motion trajectories for the robot’s pelvis and feet. After that, the angles of the leg joints can be calculated by solving the problem of inverse kinematics. Then these angle values are transferred as control signals to the robot motors. Therefore, the algorithm of the developed module ensuring the motion of the AR-600 anthropomorphic mechanism comprises the following sequence of operations.

First of all, it is necessary to determine desirable coordinates for the robot’s feet in compliance with the goal of the robot’s movement. In order to prevent falling, the zero moment point coordinates should not leave the supporting surface. Judging from this condition, the ZMP coordinates are set as the coordinates of the center of the stance leg foot.

The zero moment point trajectory for the robotic platform is set based on the beforehand determined feet coordinates and the switching sequence of the stance leg. These coordinates are used as an entry parameter for the preview regulator according to the described method [7]. The time segment of the calculation window of the walking pattern generation controller determines the number of counts N and sampling time T. An output value is the trajectory of the robot’s center of mass (CoM) that ensures the desired trajectory of the zero moment point and maintenance of the robot’s balance during movement. Figure 2 shows an example of the robot’s CoM motion trajectory according to the sequence “half-step with the left leg (LL) → step with the right leg (RL) → step with the LL → step with the RL → half-step with the LL”, direction - forward, step size - 200mm.

Figure 2. Motion trajectory of the robot’s center of mass obtained via ZMP preview control.
(a) Motion along the sagittal axis. (b) Motion along the frontal axis.

The motion trajectory of the lower extremities can be obtained based on the known feet coordinates and the previously obtained motion trajectory of the robot’s center of mass (figure 3).

![Motion trajectory graphs](image)

**Figure 3.** Motion trajectory of the robot’s feet in relation to the origin of coordinates combined with the robot’s relative center of mass. (a) Along sagittal axis Z, “forward-backwards”. (b) Along frontal axis X, “to the left – to the right”.

Changes in the position of the robot’s center of mass when the extremities move are neglected. The robot’s relative center of mass (approximately center of the pelvis) in the process of walking is at a constant height.

The feet motion trajectory along the vertical axis is set based on the information on the current switch leg, step width, lift height of the extremity and the number of points comprising the forming trajectory. Two mechanisms were used to build this trajectory: trajectory plotting based on the adaptively definable polynomial and half-circle trajectory plotting. The problem of inverse kinematics was solved via the FABRIK method [9].

Figure 4 summarizes the obtained walking algorithm for the AR-600 anthropomorphic platform.
5. Results analysis
Achieving the stable walking of the robotic platform requires the preliminary adjustment of calculated parameters. The time segment of the calculation window of the walking pattern to the generation controller determines the number of counts N and sampling time T. The selection of N and T also depends on the capacity of the computer used, as N determines the dimension of matrixes used in calculations. Calculating high-dimension matrix equations is very time-taking, and it is hard to carry out such calculations online. At the same time, choosing an insufficient number of counts for the planned time segment leads to relatively significant variations in the angle value per counting and impairs the smooth motion of the robot’s extremities.

During the experiments, the authors determined the optimal number of counts per robot’s step, which ensured a sufficient motion speed, smooth motion of the robot’s lower extremities, natural movements as well as the possibility to perform calculations online with due account for the computational capabilities of the hardware used: N = 400 number of counts of the process controller buffer, 100 counts per step, T = 0.011. With that, the maximum step length ensuring natural walking and requiring no significant preliminary knee-bend amounted to 50 cm and the robot’s speed of motion was 0.455 m/s in this case. The average calculation time of the motion cycle was 8 milliseconds, that includes calculating the positional vectors of the supporting and swinging legs feet (sideways and forward), coordinates of the target point of the foot using these vectors, calculating the configuration of the joint positions (FABRIK) and rotation angles. The time for performing calculations and implementing the full cycle of one step (raising the swing leg, its transfer, moving the torso, placing the swing leg to the surface) for given parameters was about 1 second. This time includes the update time of the forward and inverse kinematic schemes of the mechanism (from 1 to 2 milliseconds) after each motion cycle. Algorithm of the motion cycle includes a delay, so that commands are sent to the motors at fixed times, regardless of the actual calculation speed.

During the experiments, the authors used different leg lift curves generated by the adaptively definable polynomial as well as half-circle trajectories. However, the complicated trajectories did not have any positive effect on the speed, stability or naturalness of this platform walking. The half-circle trajectory appeared to be the simplest and the most convenient solution, so it was included in the final version of the process controller.

The presented algorithm is rather flexible from the viewpoint of choosing random motion trajectories. The primary limitation is the technological specifications of the robot (maximum rotation angles of the joints). However, rapid maneuvering is impossible without the use of additional balance maintenance methods, e.g. the introduction of feedback. As can be seen from the measurements of the run time presented above, in the remaining time intervals between walking motion cycles, it is possible to integrate algorithms that interpret the current IMU readings of the mechanism to adjust joint configurations and increase stability during walking.
6. Conclusion
The experiment findings show that the solution proposed in [7] can be successfully used to implement the dynamic walking of the AR-600 anthropomorphic robotic platform. The use of the zero moment point preview control ensures stable and natural movements during walking, including the case with random motion trajectories in online mode.

Despite the differences in the structure of the HRP-2 [10], anthropomorphic platform that was used by the authors of the ZMP preview control method, and AR-600, the realized module confirms that preview control can be successfully used to generate walking patterns for anthropomorphic platforms with a wide range of structures.

The authors are going to expand the functional capabilities of the realized motion control algorithm of the AR-600 anthropomorphic platform by supplementing it with an active platform balance maintenance system, which will allow improving stability in case of the rapid maneuvering and walking on uneven surfaces by the robot.

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