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Ilya Afanasyev
Innopolis University

TOWARD A HUMAN-LIKE BIPED ROBOT GAIT: BIOMECHANICAL ANALYSIS OF HUMAN LOCOMOTION RECORDED BY KINECT-BASED MOTION CAPTURE SYSTEM

Bulat Gabbasov, Igor Danilov, Ilya Afanasyev, and Evgeni Magid

Innopolis University
Intelligent Robotic Systems Laboratory
Universitetskaya 1, Innopolis, 420500, Russia
{b.gabbasov, i.danilov, i.afanasyev, e.magid}@innopolis.ru

ABSTRACT

This paper presents biomechanical analysis of human locomotion recorded by Motion Capture (MoCap) system based on four Kinect 2 sensors and iPi Soft markerless tracking and visualization technology. To analyze multi-depth sensor video recordings we utilize iPi Mocap Studio software and iPi Biomech Add-on plug-in, which provide us visual and biomechanical human gait data: linear and angular joint coordinates, velocity, acceleration, center of mass (CoM) position, skeleton and 3D point cloud. The final analysis was performed in MATLAB environment, calculating zero moment point (ZMP) and ground projection of the CoM (GCoM) trajectories from human body dynamics by considering human body as a single weight point. These were followed by GCoM and ZMP error estimation. The further objective of our research is to reproduce the obtained with our MoCap system human-like gait with Russian biped robot AR-601M.

1. INTRODUCTION

Biped robots are going to turn into a significant part of our everyday live in the coming decades performing different operations for human support and substitution in multiple tasks. By now they have advanced mobility, flexibility, and collision-free possibilities in irregular-structured terrains and human-made environments, which usually contain doors, stairs, furniture, uneven surfaces and numerous subjects developed for human use. Although the performance of biped robot locomotion has been improved in recent years using various methods, it is still too far from being stable and energy efficient comparing with human walking [1]. Therefore the analysis of the human gait is one of the most challenging and important tasks in order to develop energy-efficient algorithms of human-like robot locomotion [2].

However, due to the kinematic and dynamic differences between a human and a humanoid robot is not feasible to apply a human gait directly to a robot [3]. First of all, humans and robots have different skeletons and amount of Degrees of Freedom (DoFs), which make impossible a direct mapping of human relative positions to the robot without a special preprocessing of the human data. Furthermore, comparing to a human body, robots have very limited capabilities in terms of constraints on relative position, velocity and acceleration for joints. In addition, robots have different kinematic characteristics like weight distribution, CoM position and so forth. Furthermore, as emphasized in [4], humans and humanoid robots are underactuated systems with no actuation between a foot and the ground. Therefore, the kinematic mismatch requires kinematic corrections with calculating joint angle trajectories. The dynamic mismatch and the problem of underactuation require advanced control of such a system [4, 5], otherwise the locomotion will be unbalanced.

As far as analyzing human gait gives important properties of fast and energy efficient walking for adaptation to biped robot applications, we register Human Motion Capture Data (HMCD) both for the whole human body and every limbs by a MoCap system. MoCap allows capturing motion parameters such as linear and angular coordinates, velocities and accelerations for limbs and joints. MoCap hardware strongly depends on motion capture technology (marker or markerless), and can use sensors with different physical principles [3]: 2D / 3D cameras for optical detection, magnetic sensors with permanent magnets and coil-receivers to register changes in a magnetic field, mechanical exoskeletons for direct tracking the joint angles or based on accelerometers and gyroscopes inertial sensors. Optical MoCap systems are based on capturing 2D image using several cameras and then finding 3D model by triangulation with the help of active/passive markers or without them [3]. Taking into an account the low cost and exhaustive functionality, we selected a markerless optical MoCap system based on four depth sensors Kinect 2 and iPi Soft software package[1].

The biped/human locomotion balance can be estimated in terms of static (GCOM) and dynamic (ZMP) stabilities [6] that lead to setting up some constraints on these values. Then HMCD can be spread to balance humanoid robot by guiding the foot motion trajectory with the ZMP constraints [4] or by minimizing the angular momentum at the CoM to simplify ZMP and CoM connections [5].

In this paper we provide the biomechanical analysis of human locomotion recorded by Kinect-based motion capture system, calculating ZMP and GCoM trajectories from human body dynamics with estimating their errors. The static and dynamic criteria will be used for further HMCD reprojection to the human-like gait of Russian biped robot AR-601M, yielding its stable, energy efficient and natural movements.

The rest of the paper is organized as following. Section 2 describes our system setup, consisting of Kinect-based MoCap setup, iPi Mocap Studio software and AR-601M robot. Section 3 considers the MoCap measurement technique, including MoCap calibration, data acquisition and processing with iPi Soft. Section 4 presents the calculations of human ZMP and GCoM trajectories with accuracy estimation based on MoCap measurements. Finally we conclude and discuss the future steps of our research.

[1] Motion Capture software, supporting markerless technology from Russian company iPi Soft, http://ipisoft.com

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2. SYSTEM SETUP

2.1. MoCap based on Kinect System

We selected markerless optical MoCap system based on four Kinect 2 sensors[2] in order to record human locomotion (see, a scene configuration in Fig. 1). Kinect sensor has infrared projector and camera, which play a role of a depth sensor, giving a video and the distances to the points of human body inside a scene as the Kinect outputs. Kinect-based MoCap system allows reconstructing of a 3D model of a human body with a skeleton and studying linear and angular motions of the body, its limbs and joints in order to reproduce the human locomotion with anthropomorphic bipedal robot.

The data acquisition with MoCap is realized in several stages: MoCap calibration, video registration of human locomotion, and then non-real-time processing with iPi Soft and biomechanical data export to MATLAB. To take measurements, each Kinect sensor was connected to its own PC and thus human locomotion was recorded in a distributed system with one master PC which was used to synchronize all other records. Background evaluation was performed prior to recording.

The accuracy of single Kinect sensor depends on measurement distance and varies from several millimeters at a scene depth of 0.5 m and up to 40 mm at a depth of 5 m [7]; the compatible values for Kinect 2 sensor were obtained in [8]. We demonstrate in chapter 4 that MoCap system with four Kinect sensors succeeded to increase the accuracy of human body's CoM position estimation up to 1 m at a depth area from 1 to 5 m. It means that accuracy of skeleton reconstruction in Kinect-based MoCap with iPi Soft is quite good and is enough for human locomotion analysis.

Figure 1: *Kinect-based MoCap system: Scene configuration.*

2.2. iPi Soft package

iPi Soft software package consists of iPi Recorder free software, and iPi Mocap Studio shareware. iPi Recorder captures video data simultaneously from four Kinect cameras, whereas iPi Mocap Studio performs the post-processing of the recorded video by reconstructing a 3D model of the body motion, calculating human posture by applying inverse kinematics and matching the 3D model with the real human body position. An important part of iPi Mocap Studio is iPi Biomech Add-on plugin, which calculates from the tracked human locomotion such values as joints' coordinates, Euler angles, linear and angular velocities, accelerations, and changes of COM position with time. Next, iPi Biomech Add-on plugin allows to exports all these biomechanical data to MATLAB environment for further processing with the user algorithms.

The iPi Mocap Studio software processes the sensory data, providing the information about movements and rotations for each part of the human body, and simulates the human motion by constructing a so-called skeleton (which is being used for 3D human body model creating in order to study walking behavior at any time of locomotion). The software can also explore the kinematics and dynamics of the human body and anatomical components (bones, muscles and joints), calculating the biomechanical trajectory, CoM positions, reaction forces and joints strain. In addition to basic functions of motion capture and human body movement parameters calculation, MoCap software allows exporting 3D data, supporting biostatistical analysis and building a biomechanical model of human locomotion.

Through motion capture and analysis we study human gait in order to identify its key features, collect statistically significant data about these features and create an adequate mathematical model of human walking for its adapting to a mathematical model of AR-601M robot locomotion.

2.3. AR-601M robot description

Biped robot AR-601M (Fig. 2) is being developed by Russian company "Android Technics"[3]. It is a human-like biped robot with the height of 144 cm and weight of 65 kg, having 57 DoFs (41 active DoFs, including 12 DoFs in robot legs). Nowadays, robot has low-speed gait with GCoM trajectory laying inside the support foot while the robot is taking a step. The more detailed description of AR-601M robot is available in [9].

3. MEASUREMENT TECHNIQUE

3.1. MoCap system calibration

The MoCap system calibration computes the intrinsic and extrinsic parameters for Kinect sensors, calculates mutual Kinect localization and detects ground position. The thorough MoCap system calibration is essential because its accuracy significantly affects data quality.

The calibration process consists of the following steps[4]:

- Background evaluation. This step should be conducted without any foreign objects inside the scene.
- Video recording. During this step the MoCap system user performs waving motions with a small glowing marker. The MoCap system measures distance and position to the marker with regard to each of the Kinect cameras.
- Merging video data from different cameras into multiple camera video data.

[2] Kinect 2 for Windows is a sensor which was developed by Microsoft for the Xbox game console to interpret human positions and gestures. Kinect is equiped with a depth measurement system based on active illumination, that makes the Kinect a low cost 3D camera for applications outside the gaming industry (www.microsoft.com/en-us/kinectforwindows/)

[3] Androidnaya Tehnika (Android Technics), AR-601M belongs to a AR-600 series of robots, http://en.npo-at.com/products/ar-600

[4] iPi Soft Wiki: Calibration, http://wiki.ipisoft.com/Calibration

Figure 2: *Android Technics AR-601M robot.*

- Processing the multiple camera video by iPi Mocap Studio in order to automatically determine relative positions and orientations of the Kinect sensors.

During the calibration we faced with a problem of incorrect identification of the glowing marker position by iPi Mocap Studio due to merging the marker into the background (probably, because of the white painted walls of our laboratory room). The problem was solved by conducting the recordings in the darkness in order to make the marker distinctly visible. The iPi Mocap Studio has shown encouraging calibration results with average position error between cameras equal to 45 mm (Fig. 3).

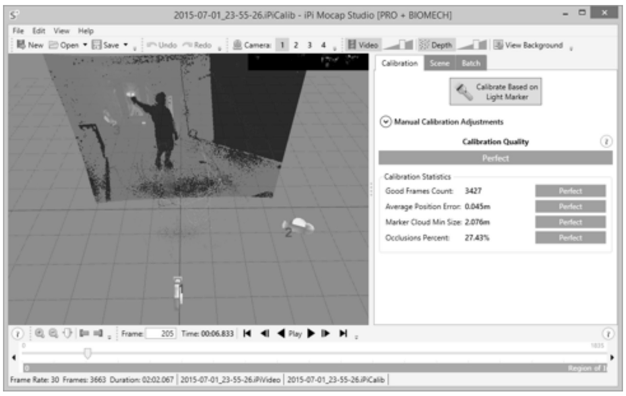

Figure 3: *Calibration process and results in iPi Mocap Studio.*

3.2. MoCap system data acquisition and processing with iPi Soft

The MoCap system data acquisition and non-real-time processing with iPi Soft consists of 4 stages: (1) Primary motion capture (merging video data from four Kinect sensors); (2) Primary data correction; (3) Noise filtering; (4) Biomechanical data calculation and exporting the data to MATLAB.

We recorded locomotion of several volunteers with MoCap, documenting also their anthropometrical data: height and weight. To initialize the motion capture with iPi Soft, a MoCap user took up a special T-pose at the center of the scene (as shown in the Fig. 4) and then started normal walking of several steps forward and backward (regular unconstrained pose of everyday locomotion, hands were moving arbitrarily) in order to provide several gait recordings.

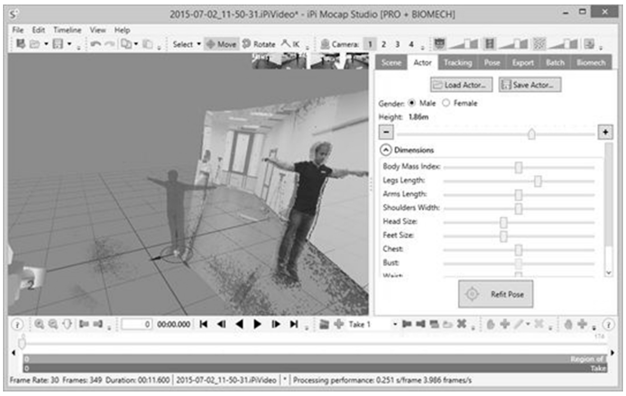

Figure 4: *Motion capture: initial T-pose capturing.*

To process each video record using iPi Mocap Studio and iPi Biomech Add-on, we executed the following steps:

1. Initial pose capturing (fitting the model of a human body with T-pose to the particular MoCap user).
2. Initial motion tracking and refitting.
3. Refinement of tracking gaps and cleaning individual frames[5].
4. Post-processing: jitter removal and trajectory filtering.
5. Computation of biomechanical characteristics and exporting them into MAT-file format (Matlab environment data files format).

In the first step we manually matched 3D model to user's T-pose as close as possible. Then we improved fitting with more accurate automatic "Refit Pose" tool.

In the second step we used the "Track Forward/Backward" tool, checking accuracy of automatic gait tracking and sometimes manually refitting a pose in the cases when iPi Mocap Studio could not perform it automatically (Fig. 5). Tracking errors may occur in a few specific video frames and then spread to multiple subsequent frames, which would result in tracking gaps. Typical examples of the problematic cases are occlusions (e.g., one hand is not visible by any of the cameras), poorly distinguishable pose (e.g., user hands are folded on chest) or very fast motion which would result into motion blur.

Once initial tracking had been performed for all relevant video frames, we began the third step which cleans out tracking errors, applying post-processing after clean-up. We refined tracking gaps using the "Refine Forward/Backward" tool. This tool slightly improves accuracy of pose matching, and can automatically correct

[5]iPi Soft Wiki: Cleaning up tracking errors and gaps, http://wiki.ipisoft.com/Clean-up

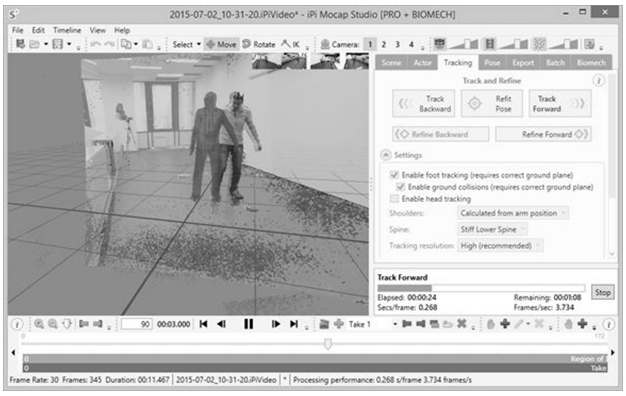

Figure 5: *Motion capture: initial tracking.*

minor tracking errors. However, it takes a bit more time than the primary tracking.

During the forth step we applied "Jitter Removal" tool to filter out noises which were caused by the limited accuracy of Kinect sensors. "Jitter Removal" filter suppresses unwanted noise and at the same time preserves sharp, dynamic motions. "Trajectory Filter" is a conventional digital signal processing tool, filtering out minor noise that remains after "Jitter Removal" filter.

In the last (fifth) phase we exported biomechanical characteristics of the user gate from iPi Mocap Studio and iPi Biomech Add-on into MATLAB environment. We are planning further processing, filtering, and developing AR-601M robot locomotion model using also MATLAB/Simulink tools.

3.3. Human motion kinematic and dynamics parameters

As was previously mentioned, for each joint we calculated coordinates, Euler angles, linear and angular velocities, accelerations, quaternion and rotation matrices using iPi Mocap Studio and iPi Biomech Add-on plug-in. The human model in iPi Mocap Studio consists of 15 joints and each such joint is considered as a ball joint with 3 DoFs. The default iPi skeleton in T-pose is shown in Fig. 6[6]. The tool is even capable of tracking separate fingers positions; however, due to the limited accuracy of Kinect 2 sensors, the resulting data is not enough accurate.

As we further describe in Section 4, we use the CoM coordinates and accelerations data from Biomech Add-on plugin for a human ZMP trajectory calculating in MATLAB. To do it, we exported biomechanical characteristics into MAT-formatted file. Next, we selected a time period where the MoCap user is walking forward, matching X-axis with forward direction and Z-axis with right hand direction (on default, Y-axis has upward direction).

4. MOCAP-BASED HUMAN ZMP CALCULATION

4.1. ZMP from human body dynamics as a single weight point

The static biped/human locomotion criterion means that the gait can be estimated as statically stable and balanced if the GCoM trajectory falls within the foot support area (support polygon) [10]. The dynamic biped/human locomotion criterion is formulated by

[6]iPi Soft Wiki: Animation export and motion transfer, http://wiki.ipisoft.com/Animation_export_and_motion_transfer

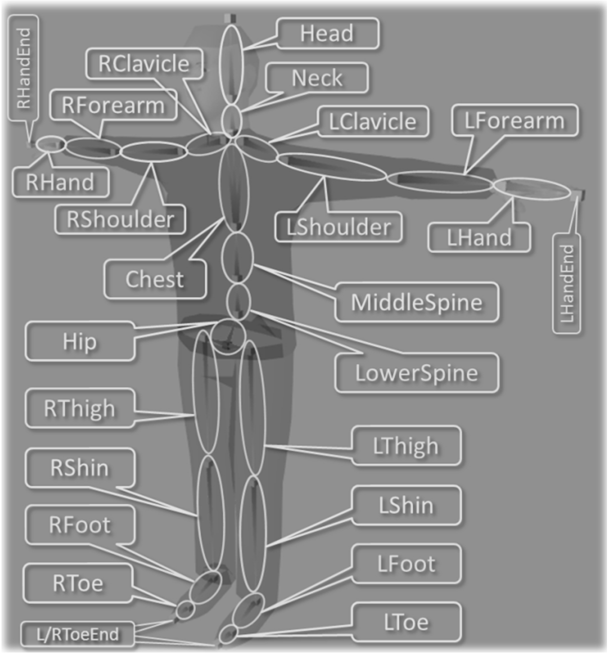

Figure 6: *The default skeleton in iPi Mocap Studio with limb names. Courtesy of iPi Soft company.*

the term of the zero moment point (ZMP) [11]. ZMP is a point on the ground under the foot where the ground reaction force will completely reduce the effects of forces and moments on the foot from the rest of the body [11]. ZMP is estimated as a dynamical equivalent of the GCoM: when the ZMP is located under the foot the system is stable; otherwise the robot/human will fall down to the ground.

A rough approximation of biped locomotion by a so-called cart-table model [12] allows to calculate ZMP as a function of CoM position and accelerations, assuming that CoM height ($\hat{y}$ in eq.1) remains the same during locomotion:

$$\begin{cases} x_{zmp}(t) = x_{com}(t) - \frac{\hat{y}}{g}\ddot{x}_{com}(t) \\ z_{zmp}(t) = z_{com}(t) - \frac{\hat{y}}{g}\ddot{z}_{com}(t) \end{cases} \tag{1}$$

where x_{zmp}, z_{zmp} are coordinates of ZMP. Next, we applied eq.(1) to the data which was exported into MATLAB from iPi Biomech Add-on plugin.

4.2. CoM and ZMP accuracy estimation technique

As far as Kinect-based MoCap adds an error to the measurement parameters, the resulting estimations of GCoM acceleration and coordinates are the non-stationary stochastic process, which could be represented with the following equations:

$$\begin{cases} x_{com}(t) = x_{T_{com}}(t) + o_x(t) \\ z_{com}(t) = z_{T_{com}}(t) + o_z(t) \\ a_{xcom}(t) = a_{T_{com}}(t) + o_{ax}(t) \\ a_{zcom}(t) = a_{T_{com}}(t) + o_{az}(t) \end{cases} \tag{2}$$

where x_{com}, z_{com} are the measured CoM coordinates; $x_{T_{com}}, z_{T_{com}}$ are true CoM coordinates; $o_x(t), o_z(t), o_{ax}(t), o_{az}(t)$ are stochastic errors.

To calculate the absolute errors of GCoM coordinates and acceleration measurements we use unbiased estimation of the standard deviation. E.g. the measurement error of x coordinate of CoM in eq.(2) is calculated with the formula:

$$\Delta x_{com} = \sqrt{\frac{\sum_{i=0}^{N}(x_i - M(x,t))^2}{(N-1)}} \tag{3}$$

where $M(x,t)$ is mathematical expectation (i.e. our estimation of the true value) for x coordinate of CoM.

As far as human body is moving in 3D space, the mathematical expectation of CoM along x-coordinate varies with time. Therefore we smooth out the MoCap-measured data (dashed curve, Fig. 7) with a moving average in order to estimate the mathematical expectation (solid curve, Fig. 7).

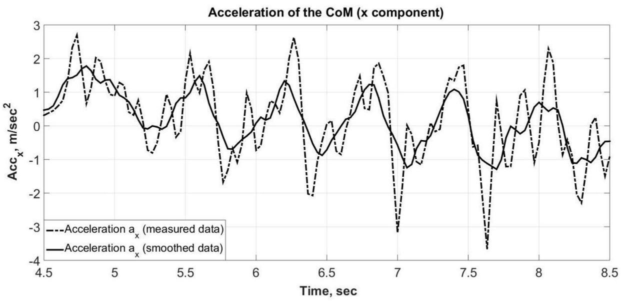

Figure 7: *Measured GCoM acceleration along the x-axis (dashed curve) and its smoothed estimation (solid curve)*

The total ZMP error for the measurements is calculated with the formula:

$$\Delta ZMP_x = \sqrt{(\Delta x_{com}^2 + (\frac{\hat{y}}{g}\Delta a_{xcom})^2)} \tag{4}$$

where $\hat{y}$ is average CoM position along the vertical Y-axis.

5. RESULTS ON ZMP TRAJECTORY CALCULATION

5.1. ZMP and GCoM trajectories from human body dynamics

The results of ZMP and GCoM trajectories calculations on the ground plane which were computed from human body dynamics (based on the simplified approximation of the human body as a single weight point) are shown in Fig. 8. The solid curve represents the ZMP trajectory and the dashed curve represents the CoM projection trajectory on the ground plane. The footsteps (i.e., particular footprints) were approximated by ellipses taking into an account RFoot, RToe and RToeEnd coordinates (according to Fig. 6).

Figure 8 demonstrates that both GCoM and ZMP trajectories are localized close to the footsteps and support polygons. It means that the human gait was properly balanced, satisfying the criteria of static (GCoM) and dynamic (ZMP) stability [6], except the final part of the trajectory at the coordinate 2 m, where ZMP curve lies outside of the support area. Figure 8 also shows that ZMP trajectory has significant deviations nearby footstep positions, which could be explained with the limitations of MoCap system measurement accuracy.

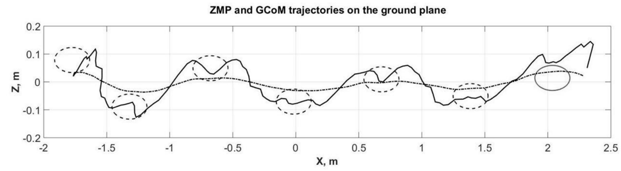

Figure 8: *ZMP trajectory (solid curve), GCoM trajectory (dotted curve) and footstep representations (ellipses) on the ground plane. The human walking direction is x-axis direction.*

5.2. CoM and ZMP accuracy estimation

The GCoM measurement error was estimated as a standard deviation with eq.(3) and the typical values which were obtained with this equation are:

$$\begin{cases} \Delta x_{com} \approx 1cm \\ \Delta z_{com} \approx 1cm \end{cases} \tag{5}$$

The total ZMP error was computed according to the eq.(4). The values evaluated with this method are:

$$\begin{cases} \Delta ZMP_x \approx 7cm \\ \Delta ZMP_z \approx 7cm \end{cases} \tag{6}$$

The total ZMP measurement errors estimated from the human body dynamics and acquired by Kinect-based MoCap system are shown in Fig. 9 together with ZMP (solid curve) and GCoM trajectories (dashed curve) on the ground plane.

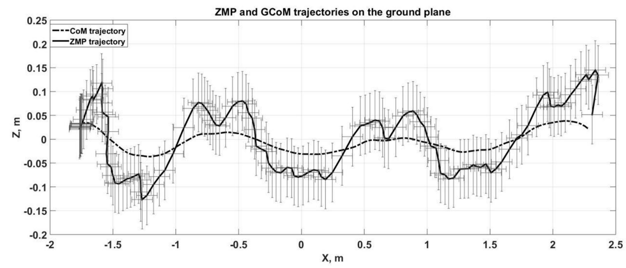

Figure 9: *ZMP (solid curve) and GCoM trajectories (dashed curve), including the total ZMP errors, estimated from human body dynamics.*

6. CONCLUSION AND FUTURE WORK

This paper is focused on the analysis of human locomotion. The human locomotion data was recorded with a Motion capture (MoCap) system which consists of four Kinect 2 sensors and iPi Soft markerless tracking and visualization technology. The human locomotion balance was further estimated in terms of static (GCOM) and dynamic (ZMP) stabilities. The analyzed GCoM and ZMP trajectories were located close to the footsteps (footprints) and the corresponding support polygons, allowing to conclude that the human gait was statically and dynamically stable with keeping proper balance. The results of calculations of human ZMP and GCoM trajectories on the ground plane which were computed from human body dynamics (based on the simplified approximation of the human body as a single weight point) have demonstrated the total measurement errors of 1 cm for CoM projection and 7 cm for ZMP trajectory estimations.

Although the accuracy of a single Kinect sensor depends on measurement distance and varies from several millimeters at a depth of 0.5 m and up to 4 cm at a depth of 5 m, the MoCap system with four Kinect sensors increases the accuracy of human body's CoM position up to 1 cm at a depth area from 1 to 5 m. It gives a quite good accuracy of skeleton reconstruction in Kinect-based MoCap with iPi Soft that is suitable for the task of human locomotion analysis.

Through motion capture and analysis we study human gait in order to identify its key features, collect statistically significant data about these features and create adequate mathematical models of human and robot locomotion. The static and dynamic criteria will be used for further Human Motion Capture Data (HMCD) re-projection to the human-like gait of Russian biped robot AR-601M, yielding its stable, energy efficient and natural movements. We are planning further processing, filtering, and developing the robot locomotion model using MATLAB/Simulink tools.

7. ACKNOWLEDGEMENTS

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