Swing Leg Trajectory Optimization for a Humanoid Robot Locomotion

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Keywords: Humanoids, Bipedal Walking, Swing Phase, Optimal Trajectory Planning, Dynamic Programming.

Abstract: The problem of walking trajectory optimisation for bipedal humanoid robots attracts many researchers because of excessive interest to bipedal locomotion. The main focus is usually on robot dynamics and trajectory planning for predefined walking primitives. In contrast to other works, our paper targets to obtain optimal walking primitive for swing leg trajectory of bipedal humanoid robot walking. Optimal walking primitives are obtained taking into account velocity and acceleration physical limitations of each joint and are derived for different walking parameters such as step size and hip height. To obtain a desired time-optimal trajectory dynamic programing approach is used. It is shown that a new trajectory is performed within a shorter time comparing with commonly used locomotion trajectories for bipedal robots control. The results allow us to assign walking parameters and corresponding walking primitive that maximize robot velocity for predefined environment constraints.

1 INTRODUCTION

To create a robot that could successfully operate in environments that were originally designed for humans, research community addresses to human-like robots also known as humanoids. The growing interest in the development of humanoids has been observed for more than several decades (Channon et al., 1992; Goswami, 1999; Katić and Vukobratović, 2003). The objective of research community is to create a robot, which will operate with a human or instead of him/her in dynamic environments, including offices, factories, private and public compartments, and be able to help in performing various operations originally adapted for a human as an actor.

Bipedal walking is one of the most natural and attractive types of humanoid locomotion, since bipedal robots provide more potential and flexibility to move through rugged terrains and complex environments, which create considerable difficulties for wheeled or tracked robots due to their limited locomotion capacities. On the other hand, bipedal robots are less stable and may fall down while performing even simple activities in rather standard for a human environment where we efficiently operate on a daily basis. Therefore, bipedal locomotion stability related research keeps attracting many researchers nowadays in order to propose good robot locomotion control algorithms and to prevent a biped robot from falling down (Akhtaruzzaman and Shafie, 2010, Escande et al., 2013).

Among the variety of open research questions in humanoids, robot body motion gains significant attention of research community (e.g., (Hofmann et al., 2009, Ude et al., 2004)), since it has a direct impact on robot dynamics and stability. Here, the key interest of researchers is related to dynamics and trajectory planning for predefined walking primitives (Kajita et al., 2001). However, the leg trajectory optimality in a swing phase - a state in which the lifted leg has no contact with a supporting plane and swings forward - has not been studied in details yet. Similar problems arise in robotic manipulators, when time-optimal trajectory for a particular technological task should be obtained (Pashkevich et al., 2002). In humanoids, researchers usually use predefined smooth trajectories for swing foot motions, such as cycloids or third order polynomials (Ha and Choi, 2007). Because during the walking process a swing foot has a maximal Cartesian speed among all humanoid limbs, leg joint limitations play a key role in a humanoid robot overall walking speed. In our paper we propose a simple and effective method for searching of an optimal swing leg trajectory within

Khusainov, R., Klimchik, A. and Magid, E.
Swing Leg Trajectory Optimization for a Humanoid Robot Locomotion.
DOI: 10.5220/0006011401300141
In *Proceedings of the 13th International Conference on Informatics in Control, Automation and Robotics (ICINCO 2016) - Volume 2*, pages 130-141
ISBN: 978-989-758-198-4

physical joint limits using dynamic programming approach. Optimality of the trajectory is estimated with a step traveling time criterion and also takes into account velocity and acceleration limits of leg joints. The obtained walking primitives with different walking parameters (hip height, step size and time) are used further to obtain optimal desired walking primitive with a maximal robot velocity for predefined environment constraints.

2 PROBLEM STATEMENT

There exist numerous approaches that are used for bipedal robot locomotion control such as Central Pattern Generation (Khusainov et al., 2015, Righetti and Auke Jan, 2006), Neural networks, rule based algorithms (Wright and Jordanov, 2014), gradient optimisation technique (Ratliff et al., 2009) and others. One of the most challenging strategies is so-called passive-walkers (Collins et al., 2005, Collins et al., 2001), which in some cases could be controlled by a single actuator (Hera et al., 2013). The pioneer method in modelling of a bipedal robot walking and the most popular one is an analytical approach, which defines equations for the robot locomotion under some constraints induced by humanoid stability. This approach has been used since 1970, when Miomir Vukobratović proposed a so-called Zero Moment Point (ZMP) stability constraint (Vukobratović and Stepanenko, 1973). Currently, ZMP controller based walking is the most popular approach, which generates target trajectory of a humanoid robot in a way that ZMP lies inside support polygon (Vukobratović and Borovac, 2004, Sardain and Bessonnet, 2004). Here, ZMP is a specific point on a moving surface, where superposition of contact and inertia forces does not produce horizontal moment. In practice, the robot remains in a stable configuration only if ZMP remains inside of a support polygon (Erbatur and Kurt, 2009). ZMP stability constraint equations are used to determine trajectory of Center of Mass (CoM) for the robot (Mitobe et al., 2000). ZMP approach is also used for trajectory generation based on Inverted Pendulum Model (Majima et al., 1999, Khusainov et al., 2016b) and Preview Control (Kajita et al., 2003, Park and Youm, 2007). In these methods CoM trajectory is a result of analytical solution of dynamic equations for minimisation of ZMP error in feedback control.

To the best of our knowledge, all algorithms for bipedal robot stable walking select motion of leg joints, which determine a swing leg movement, without considering optimality of a trajectory. For example, for NAO robot locomotion Motoc et al.(Motoc et al., 2014) use a cycloid trajectory to generate smooth motion, which is characterized with zero velocity at the beginning and at the end of the motion. Rai and Tewari (Rai and Tewari, 2014) use a polynomial interpolation to obtain a swing leg trajectory, assuming that robot's CoM movement is given. These approaches do not take into account joint constraints and obtained trajectories do not satisfy optimality from energy consumption point of view. Therefore, the calculated trajectories of a swing leg may be unattainable in practice because of velocity/acceleration/jerk limits in joints and thus would lead to wrong foot positioning, i.e. desired and real trajectories would have a weak correspondence. As a result, positioning errors accumulate with each new step, which is a critical issue for autonomous robots without global positioning feedback.

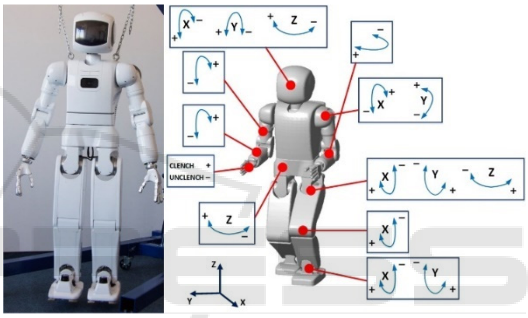

Figure 1: Full-size humanoid AR-601M (left) and its kinematic structure in Matlab/Simulink environment (right).

For our research we use anthropomorphic robot AR-601M (Fig. 1) with 41 active degrees of freedom (DoF), although we currently involve only 12 joints (6 in each pedipulator) in the walking process. Inverted Pendulum Model (Majima et al., 1999) with ZMP stability constraint is used to generate CoM trajectory. Here, six DoF of the supporting leg are fully defined by CoM movement. For straightforward motion it is assumed that in a frontal plane a swing leg is perpendicular to the ground (or support plane) at each time instance, a swing foot is parallel to the ground, and a hip height remains constant during the locomotion. These assumptions arise from human natural walk analysis (Gabbasov et al., 2015) and are widely applied in experimental works for biped locomotion (Yussof et al., 2008). Taking into account that a desired trajectory of a swing leg lies in a sagittal plane, all joint coordinates of the swing leg are uniquely defined for any foot and hip locations. In this case the optimal trajectory problem is reduced to 2DoF system. Thus, the swing leg could be represented as a simple two-link system with hip and knee joints. The corresponding to AR-601M robot leg parameters link lengths are equal to 280 mm each. Since in our models robot's body moves at a constant speed, for simplicity, we ignore body movement and we assume a fixed position of the hip joint. This means that the considered problem is represented in a moving coordinate system. The trajectory of the swing leg (solid line), support leg placement (dashed line) and model parameters are shown in Fig. 2.

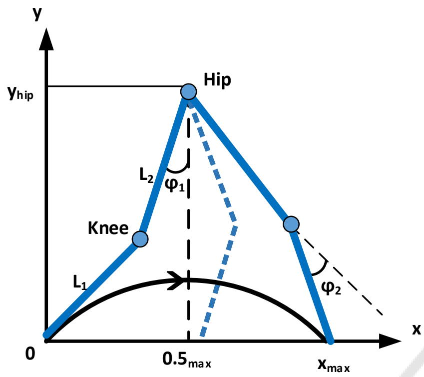

Figure 2: Step motion of the swing leg in sagittal plane.

The primary research problem can be formulated as follows: for given start and end points of a swing leg and hip location, find an optimal trajectory, which minimizes a selected cost function. Moreover, joint angular velocities and angular accelerations during locomotion should not exceed their maximal values. The secondary research problem could be formulated as follows: for a given robot and predefined obstacles (which could be stepped over by the robot), obtain optimal walking primitive that maximizes robot speed in a given environment.

3 OPTIMISATION CRITERIA

There are different approaches to define cost function in optimal trajectory search problem. For example, Nakamura et.al. in (Nakamura, 2004) minimized energy consumption, which can be written in the form:

$$\sum_{i=1}^{2}\left[\tau_i\dot{\theta}_i+\gamma\tau_i^2\right]dt \qquad (1)$$

where τ_i is joint i torque, $\dot{\theta}_i$ is joint i velocity, γ is an empirical constant. The first term in (1) corresponds to mechanical work, which is performed to move dynamic system. The second term corresponds to heat emission in each joint due to torque generation. It was shown, that optimal trajectory which could be found in such a way well agrees with experimental data of human locomotion. Yet, while obtaining a swing leg trajectory, the authors do not take into account maximum joint velocity and acceleration limitations, which actually provide critical constraints for a real robot. A selected trajectory could be energy optimal in theory, but if the robot's motors could not supply required by such trajectory torques, the physical robot will fail to perform such trajectory (Khusainov et al., 2016b).

In practice, walking speed is one of the most important performance measures for bipedal robots. Walking speed could be unambiguously calculated, while energy consumption calculation is not that obvious as it depends on many factors; e.g., energy is mainly consumed in supporting leg joints, since they have much higher actuating torques than swing leg joints (in our work only swing leg motion is considered). In addition, energy consumption strongly correlates with step time: the faster a swing leg moves for a given step length, the lower is its energy consumption. Therefore, minimization of each step time is a critical issue to be considered, and it is the core contribution of our paper. Step time can be evaluated as

$$t=\int_S (1/V)\,dS \qquad (2)$$

where V is a foot speed in Cartesian space and dS is the foot path. Time t is calculated numerically by dividing the trajectory into a finite number of intervals and further summing up over all intervals.

4 OPTIMAL TRAJECTORY SEARCH ALGORITHM

Optimal path for a bipedal robot swing leg could be found with regard to different optimization techniques. For example, in (Nakamura, 2004) spline genetic algorithm (GA) was used to determine joint torques for several points on the trajectory, which were further used to interpolate joint torques for remaining trajectory points introducing third order splines. The main drawback of this approach is the fact that genetic algorithms in general are not efficient in finding a global minimum for continues functions with multiple local minima (Renders and Flasse, 1996). An alternative approach for 6 DoF manipulator has been used by Tangpattanakul and Artrit (Tangpattanakul and Artrit, 2009)who utilised a heuristic optimization method to find optimal trajectory with Harmony Search algorithm. The obtained trajectories were smooth and complied all kinematic constraints (both for velocity and acceleration). However, in this approach only 6 via-points have been used along the trajectory, which limited its utilisations because of potential problems between via points.

To overcome the above mentions limitations, in this study, an optimal path is calculated using dynamic programming approach (Si et al., 2009). The key idea of this approach is to divide a large problem into sub-problems of lower dimensions corresponding to a transition between two via points, to solve each of these sub-problems once and to store the solutions. Advantages of this method are robustness and computational efficiency compared to other methods. Illustration of this approach for a simple case with three via points is shown in Fig. 3. To find an optimal path from node (1,1) to node (5,1) with a minimum total weight (time in the case of optimisation walking trajectory) it is required to examine all possible connections between these points. Dynamic programing approach feature is that via points are not specified exactly and can be assigned to any node point of the row. Starting from the left, for every node minimal total weight W is computed and saved together with the node on the previous layer, transition from which is optimal (green lines in Fig. 3). For example, for node (2,2) the minimal weight is 5 and the only transition from node (1,1) is possible. For node (3, 1) minimal weight is 8 (5+3), which corresponds to transition from the node (2,2). For node (3, 3) minimal weight is also 8 (5+3) and corresponds to transition from the same node (2,2) as for note (3, 1). For node (4, 3) minimal weight is 12 (8+4), which corresponds to transition from the node (3,1). Finally, we look at end point and find its optimal transition. After that, to get the optimal path, the optimal path from the last layer to the first layer is constructed. For the provided example the optimal path corresponds to the following path (red bold line in the Fig. 3): (5,1), (4,3), (3,1), (2,2), (1,1).

To transform optimal path search problem for a bipedal robot from continues optimisation problem into a directed graph it is required to assign evenly distributed nodes $p_{i,j}$ within the search space, which cover all possible trajectory paths. Here, to cover all leg locations in x and y coordinates, it is necessitated to create a two dimensional grid with $n_x + 1$ points in x direction and $n_y + 1$ points in y direction (see Fig. 4). Since the foot trajectories are considered with a certain defined height limit y_{max} and step length x_{max}, the desired search space size is equal to $x_{max} \times y_{max}$ area, which contains $n_x - 1$ via points to be assigned (a single via point per each $x = \overline{2 : n_x - 1}$, while y locations are constrained by potentially traversable by the robot obstacles only).

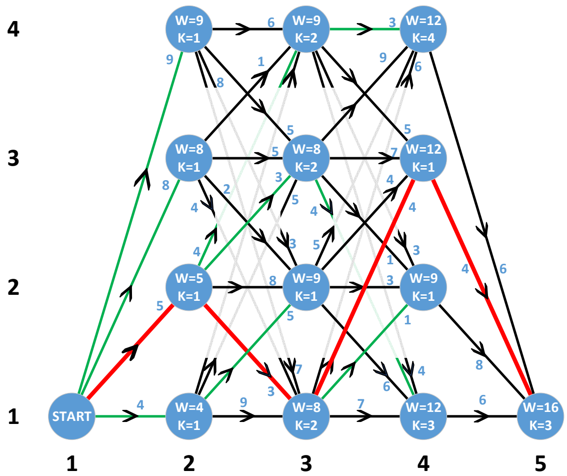

Figure 3: A directed graph for optimal path selection using dynamic programming approach.

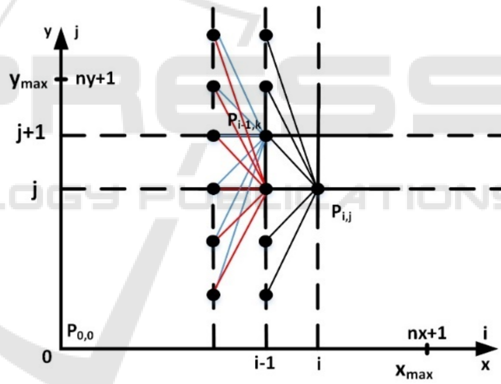

Figure 4: Building directed graph in search area by creating 2D grid.

The algorithm for finding the optimal path works as follows:

- For each node point $p_{i,j}$, $i = 1$, $j = \overline{1, ny+1}$ calculate the weight (i.e., the cost), which corresponds to the minimal time of the transition to that node from the start point $p_{0,0}$. For each node save the weight and joints angular velocities at the end point of the corresponding trajectory.
- For each node $p_{i,j}$ where $i = \overline{2, nx}$, $j = \overline{1, ny+1}$ calculate the weight of transition from $p_{i-1,k}$ node, where $k = \overline{0, ny+1}$. Find k_{min}, for which

the sum of the calculated weight for a transition from $p_{i,\mathrm{k}_{\min}}$ and total weight of $p_{i,\mathrm{k}_{\min}}$ node is minimal. For each node $p_{i,j}$ save $k_{\min}$, the total weight and joints angular velocities, which are calculated for the transition from $p_{i,\mathrm{k}_{\min}}$ to $p_{i,j}$

- For node $p_{\mathrm{nx}+1,0}$ (the end point) calculate the weight of the transition from $p_{\mathrm{nx,k}}$, where $k=\overline{0,ny+1}$. Find $k_{\min}$, for which the sum of the calculated weight and the total weight of $p_{\mathrm{nx,k}_{\min}}$ node is minimal.
- Obtain an optimal trajectory by tracking backward $\mathrm{k}_{\min}$ values for each node:

$$p_{nx+1,ny+1} \to p_{nx,k_{\min}^{nx+1}} \to p_{nx-1,k_{\min}^{nx}} \to \dots \\ \dots \to p_{1,k_{\min}^{2}} \to p_{0,0} \tag{3}$$

where $k_{\min}^{nx+1}$ is the optimal track for $p_{nx+1,ny+1}$ node.

Since the transition time between two node points is used as a cost function, it is required to calculate minimal traveling time from node $p_{i-1,\mathrm{k}}$ to node $p_{i,j}$ taking into account velocity and acceleration limits. First, joint angles' increments are calculated for each transition between two adjacent nodes. Then we mark a joint as *active* if it has larger absolute value of angular increment for a given transition. Without loss of generality let's assume that joint 1 is active and joint 2 is passive. Assuming that an active joint for each interval moves either with a constant speed or a constant acceleration (depending whether it reaches the maximum velocity on previous interval), the joint movements could be described as follows:

$$\Delta\varphi^{(i)} = \omega_s^{(i)} t + 0.5 a^{(i)} t^2 \tag{4}$$

$$\omega_e^{(i)} = \omega_s^{(i)} + a^{(i)} t \tag{5}$$

where i=1 for an active joint and i=2 for a passive joint, $\Delta\varphi$ is an angular increment, ω_s and ω_e are angular velocities at start and end of the interval respectively, a is an angular acceleration (assumed to be constant within the interval) and t is a transition time.

In order to describe all possible relations between active joints on adjacent intervals, three different cases for calculating transition time should be considered:

Case 1: Maximal Velocity. If an absolute angular velocity of an active joint in $p_{i-1,\mathrm{k}}$ node is equal to maximum value $\omega_{\max}$ and its sign is equal to the sign of angular increment $\Delta\varphi$, then $t = \left|\Delta\varphi^{(1)}\right| / \omega_{\max}$, $a^{(1)} = 0$, $\omega_e^{(1)} = \omega_s^{(1)}$. Substituting t into equations (4) and (5) we obtain $a^{(2)}$, $\omega_e^{(2)}$. It should be emphasized that if the sign of angular increment $\Delta\varphi$ is opposite to the current velocity sign at the interval beginning than either Case 2 or Case 3 should be applied.

Case 2: Maximal Acceleration. If an absolute angular velocity of an active joint in $p_{i-1,\mathrm{k}}$ node is below its maximum value $\omega_{\max}$ or its sign is opposite to the sign of angular increment $\Delta\varphi$, then we substitute $\Delta\varphi^{(1)}$ into equation (2) with $a^{(1)} = sign(\Delta\varphi^{(1)}) a_{\max}$ and solve the second order equation with respect to t:

$$t = \frac{-w_s^{(1)} \pm \sqrt{(w_s^{(1)})^2 + 2a^{(1)}\Delta\varphi^{(1)}}}{a^{(1)}} \tag{6}$$

Next, we select the lower positive root of the above equation and calculate $\omega_e^{(1)} = \omega_s^{(1)} + a^{(1)} t$. If $\left|\omega_e^{(1)}\right|$ is less than or equal to $\omega_{\max}$, than $a^{(1)}$ and $\omega_e^{(1)}$ are equal to the calculated values. Finally, we substitute t into equations (4)-(5) to obtain $a^{(2)}$, $\omega_e^{(2)}$.

Case 3: Reaching Maximal Velocity. If Case 1 condition is not satisfied and $\left|\omega_e^{(1)}\right|$ in Case 2 is greater than $\omega_{\max}$, than $\omega_e^{(1)} = sign(\Delta\varphi^{(1)})\omega_{\max}$, $t = 2\Delta\varphi^{(1)} / (\omega_e^{(1)} + \omega_s^{(1)})$, $a^{(1)} = (\omega_e^{(1)} - \omega_s^{(1)}) / t$. We substitute t into equation (4)-(5) to obtain $a^{(2)}$, $\omega_e^{(2)}$.

Figure 5 demonstrates all three cases which are described above. For all cases we verify if the calculated joint angular accelerations and velocities are below their maximal values. If this condition cannot be satisfied, such transition is excluded from a possible path of the swing leg.

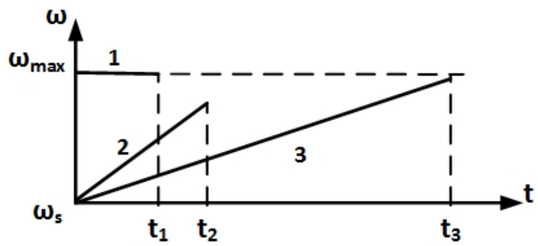

Figure 5: Three cases of angular velocity behavior: (1) maximal velocity; (2) maximal acceleration; (3) reaching maximal velocity

5 SELECTING OPTIMAL WALKING PRIMITIVE

It should be mentioned that for each given step length and hip height a unique optimal walking primitive is obtained. These primitives will have different weight (traveling time) even in a case of an identical step length but unequal hip heights. As a result, assigning particular initial walking parameters affects robot speed capacity. Therefore, considering different step size and hip height it is possible to estimate robot's potential and to select the most appropriate primitive, which ensures the best performance in terms of robot's speed. Another important issue that should be also considered addresses particular characteristics of the environment, i.e. presence of different obstacles on the robot's way, which could not be easily circumambulated. To obtain an appropriate walking primitive for negotiating a traversable obstacle (i.e. stepping over such obstacle) the following algorithm could be utilized.

Step 1: Specifying Constrains. Based on a visible and technically traversable obstacle that appears on the robot's way, define feasible legs locations for bipedal robot. The obstacle can be approximated with rectangles and triangles that cover all unreachable locations – as we address only 2D case within a sagittal plane, only obstacle's height and length in robot's walking direction are considered.

Step 2: Define Walking Parameter Limits. Based on the robot geometry and current obstacle to be negotiated, it is required to obtain reasonable search intervals for step length and hip rising height, i.e. their minimal and maximal values. Parameter limits should be selected in such a way that at least one trajectory with a continuous solution of inverse kinematic problems exists between start and end locations of a swing leg. Step size should be small enough to detect extremum points.

Step 3: Finding Optimal Primitives for Each Case. For each combinations of a step length and a hip rising height obtain optimal walking primitive and traveling time using dynamic programming approach presented in Section 4. If there is no solution of inverse kinematic problem for at least one via point, it is required either to decrease step size.

Step 4: Selection of an Optimal Walking Primitive. For each combination of walking parameters estimate walking speed (in Cartesian space) and select the optimal combination with regard to a particular optimization criterion (i.e., the one with the highest walking speed).

The above presented algorithm could be applied for selecting optimal walking primitives for humanoid robots with at least two DoFs within a sagittal plane for each leg or could be further extended for more DoF within a sagittal plane. It gives a unique solution for the assigned initial parameters of the robot and particular obstacle properties, but the results are not being directly scalable both between different robot models and obstacles because of obstacles variety and physical properties of various robots (link lengths, joint limits for velocity and acceleration etc.). Thus, particularity of robot kinematics always requires re-computing optimal primitives for each specific model's parameters and each obstacle. Nevertheless, once computed set of primitives for typical environment conditions (i.e. different traversable obstacles) for a particular robot model could be further applied for the robot control for a whole set of robot motions.

6 SIMULATION RESULTS

The simulation of the algorithm was performed within MATLAB/Simulink environment. The acceleration and velocity limits were assigned to 1 rad/s^2 and 1 rad/s respectively for each joint. These values correspond to technical characteristics of the motors, which are used in AR-601M robot. First, let us obtain optimal walking primitives for the fixed hip rising height and step length and then compare results with optimal parameters settings.

For the first case hip height was fixed to 0.5 m in order to ensure optimal locomotion speed of the robot based on our previous empirical studies (Khusainov et al., 2016b, Khusainov et al., 2016a). According to joint limits and link parameters we selected the robot step length to be 0.4 m. For these parameters hip and knee joint angles in their starting position were set to 0.1 and 0.55 rad correspondingly; at the end of the trajectory (goal position) hip and knee joint angles were set to -0.66 and 0.55 rad correspondingly. These angles define $p_{i,j}$ and $p_{i,j}$ nodes.

Next, three different cases were analysed:

(i) movement without any trajectory constraints, i.e. in an ideal case without velocity/acceleration limits the foot may move straightforwardly from a start point to an end point (Fig. 6);

(ii) movement with 0.1 m barrier (with negligible small size in the robot walking direction) in the middle of the trajectory (Fig. 7);

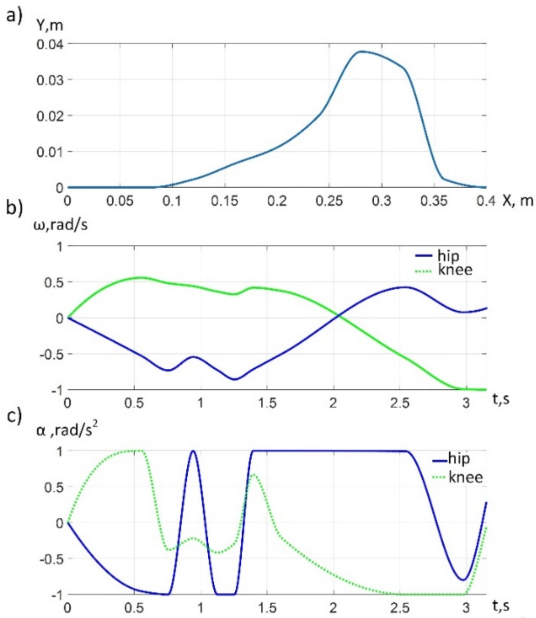

Figure 6: Optimal trajectory without obstacles for hip height 0.5 m and step length 0.4 m: (a) foot trajectory in Cartesian space; (b) angular velocity of joints; (c) angular acceleration of joints.

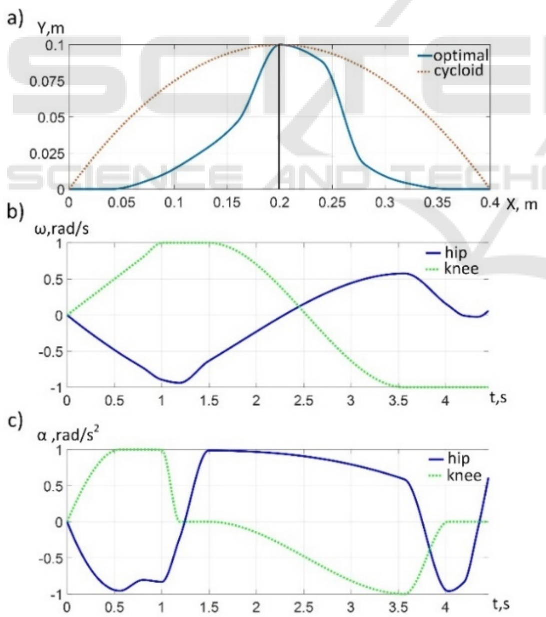

Figure 7: Trajectories with 0.1 m barrier in the middle for hip height 0.5 m and step length 0.4 m: (a) optimal foot trajectory in Cartesian space and cycloid trajectory; (b) angular velocity of joints; (c) angular acceleration of joints.

(i) movement with 0.05×0.2 m box barrier in the middle (Fig. 8).

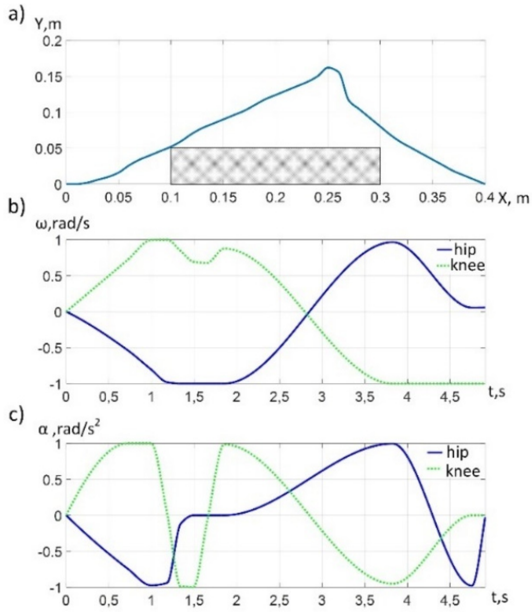

Figure 8: Optimal trajectory with 0.05×0.2 m box barrier in the middle for hip height 0.5 m and step length 0.4 m: (a) optimal foot trajectory in Cartesian space; (b) angular velocity of joints; (c) angular acceleration of joints.

The results demonstrated that for all cases the obtained Cartesian trajectories of a swing leg do not correspond to the shortest path and differ from a cycloid path, which is traditionally used in bipedal robot locomotion control. To compare our results with a cycloid path approach, we built the cycloid trajectory for (ii) case and ensured the same travelling time as for our optimal trajectory (Fig. 7a). The corresponding angular velocities are presented in Fig. 9. The simulation demonstrated that for the cycloid trajectory, the knee angular velocity exceeds maximum value and the accelerations at the beginning and at the end of the trajectory are very high. That means that in practice it is impossible to perform such trajectory within the specified time. In order to move along a cycloid trajectory, it is required to scale (increase) travelling time according to the velocity limits. Hence, the proposed algorithm succeeds to suggest a foot trajectory with a shorter time interval comparing to a typical cycloid trajectory.

In the case without trajectory constraints, the foot rises up to 0.04 m, which is caused by joint velocity/acceleration limits. It is evident that travel time in such case is minimum. The particularity of this trajectory is that the joint velocity limits are not reached (see Fig. 6b).

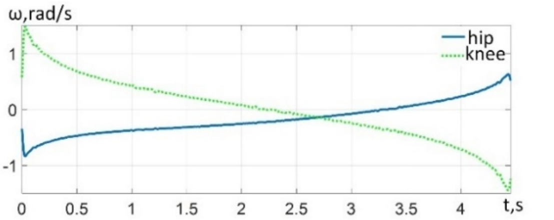

Figure 9: Angular velocities of joints for cycloid trajectory movement with 0.1 m barrier, case of for hip height 0.5 m and step length 0.4 m.

Barrier profile essentially effects optimal trajectory (see Fig. 7a and Fig. 8a). Although the (ii) case barrier is two times lower than for case (iii), the height of the optimal trajectory for case (iii) and its travel time are higher.

To compare efficiency of the obtained walking primitives with conventional cycloids, the joint speed and acceleration profiles have been obtained for cycloids as well. It should be stressed, that these profiles do not satisfy velocity and acceleration limits, and to ensure such trajectory implementation it is required to increase traveling time. In particular, for free motions without obstacles the acceleration limits have been exceeded by the factor 6, and to remain within the limits traveling time should be over 10 s, which is twice higher that for the obtained optimal trajectory. Another limitation of conventional trajectory planning approach is its sensitivity to a swing height and request to provide traveling time as an input parameter. Our proposed approach does not have these limitations and automatically estimates minimal traveling time and an optimal swing leg height.

Now, let us obtain optimal hip heights and step length for all cases considered above and compare robot performance. Speed maps for different step length and hip height are presented in Fig. 10-12. Here, lighter colour corresponds to higher speed and are preferable for robot locomotion. It is shown that Cartesian speed highly depends on the step length and hip height and varies from one case to another. It is also shown that optimal step parameters highly depend on the size of the obstacle, which appears on the robot path. In particular, for the case without obstacles optimal settings are hip height of 0.4 m and step length of 0.32 m, while for the case of box barrier the optimal step length is much higher (0.52 m) and hip height is almost the same (0.45 m).

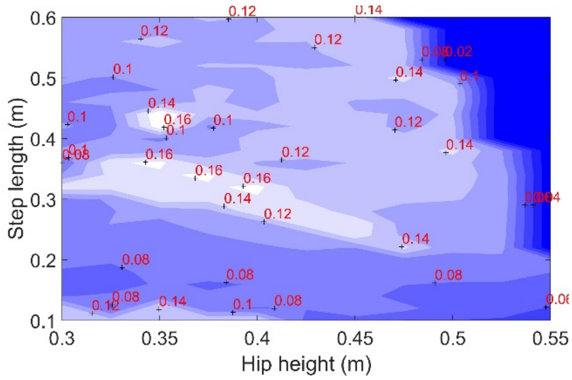

Figure 10: Robot AR601M speed map for different step length and hip height for the trajectory without obstacles.

Optimisation results are summarised in Table 1, where for the three cases an optimal hip height, a step length and a corresponding robot speed are given. For comparison purposes it also contains robot speed for the case of a fixed hip height and step length studied above. It is shown that for the case of optimal hip and step size parameters robot speed increases by 10-23%, depending how far initial parameters were from the optimal ones.

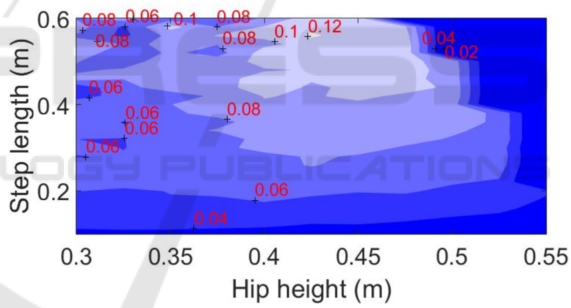

Figure 11: Robot AR601M speed map for different step length and hip height for the trajectory with 0.1 m barrier in the middle.

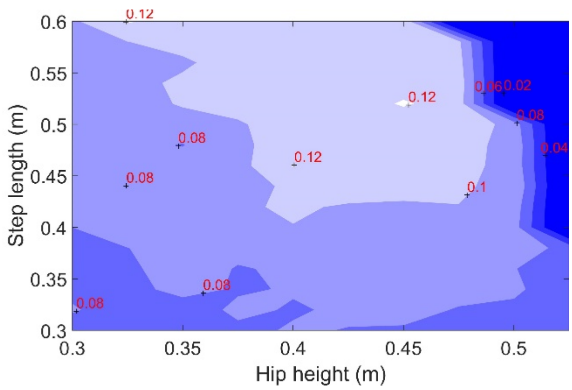

Figure 12: Robot AR601M speed map for different step length and hip height for the trajectory with 0.05×0.2 m box barrier in the middle.

Table 1: Optimal walking parameters for locomotion of bipedal humanoid robot AR-601M.

Case	Step length (m)	Hip height (m)	Speed (m/s)	
			Fixed param.*	Optimal param.**
(i) without obstacles	0.32	0.40	0.13	0.16
(ii) with 0.1 m barrier	0.56	0.43	0.09	0.12
(iii) with 0.05×0.2 m box barrier	0.52	0.45	0.11	0.12

*Fixed hip and step length parameters are 0.5 m and 0.4 m respectively

**Optimal hip height and step length parameters

For comparison purposes Fig. 13-15 contain walking primitives with joint velocities and accelerations. It is shown that in the cases (ii) and (iii) acceleration oscillations are essential (see Fig. 14c-15c), which is mainly caused by problem discretization and numerical calculation effects. Nevertheless, these vibrations do not overcome acceleration limits and will not affect robot performance.

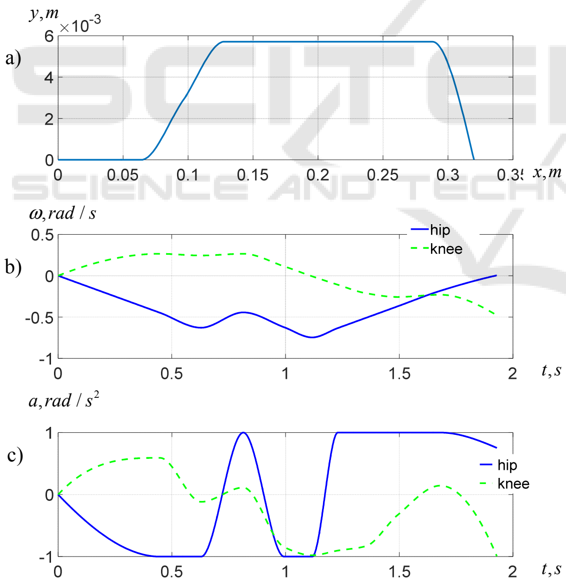

Figure 13: Optimal trajectory without obstacles for 0.4 m hip height and 0.32 m step length: (a) foot trajectory in Cartesian space; (b) angular velocity of joints; (c) angular acceleration of joints.

A rather evident fact that for an optimal robot speed without no obstacles, an optimal trajectory should be close to the ground level was confirmed by simulation results. It is clear that in practice such trajectory could be hardly implemented (in fact, it is not possible to have zero step height while locomotion), while it demonstrates efficiency of the proposed approach. With such moving primitive the robot can move with 0.16 m/s velocity instead of 0.13 that is maximal for 0.5 m hip height and 0.4 m step length. Similar tendencies are observed for all considered cases.

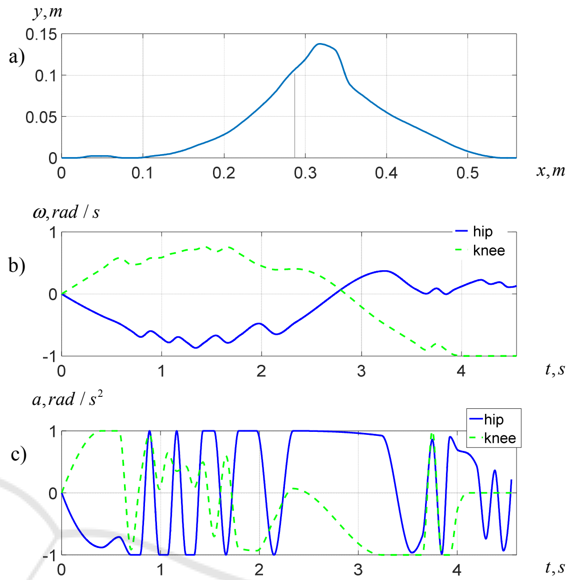

Figure 14: Trajectories with 0.1 m barrier in the middle for hip height 0.43 m and step length 0.56 m: (a) an optimal foot trajectory in Cartesian space; (b) angular velocity of joints; (c) angular acceleration of joints.

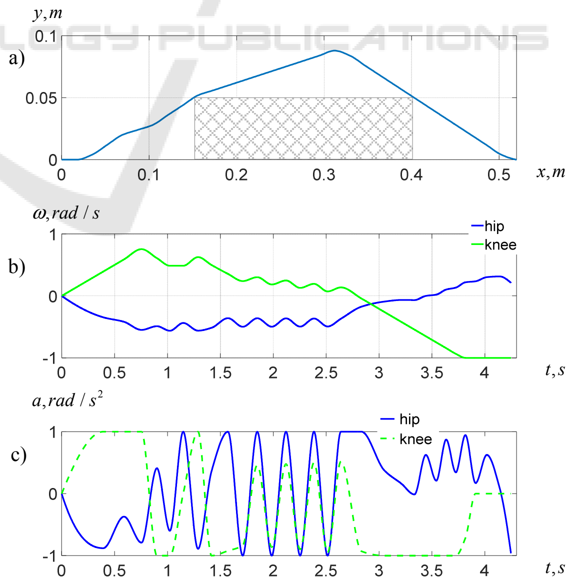

Figure 15: Optimal trajectory with 0.05×0.2 m box barrier in the middle for hip height 0.45 m and step length0.52 m: (a) an optimal foot trajectory in Cartesian space; (b) angular velocity of joints; (c) angular acceleration of joints.

7 DISCUSSIONS

In spite of numerous advantages, the proposed walking trajectory optimization approach has several apparent limitations, and the most significant one among them is ignoring of dynamic and static effects within optimization procedure. In fact, static effects (compliance errors) are not critical for the trajectory optimization since they are relatively small and could be easily compensated by integrating a feedback control from the feet force sensors. In this case the main limitation for the moving primitive is avoiding joint coordinates limits, which may not allow the robot to compensate induced compliance errors. From another side, if feedback control is not available compliance errors should be computed using linear or non-linear stiffness modelling (Klimchik et al., 2012, Klimchik et al., 2014b) and control algorithm should rely on the elasto-geometric model (Klimchik et al., 2013, Klimchik et al., 2014a). It should be stressed that stiffness parameters for real robot can be obtained from the dedicated experimental study only (Klimchik et al., 2015). So, statics effects the control algorithm, but is not critical for optimization walking primitives.

On the other side dynamic effects directly influence robot stability (Majima et al., 1999, Mitobe et al., 2000) and can be hardly compensated, since this will directly affect walking primitive profile. Since walking profile contains only foot coordinate, humanoid torso and arms could be used to additionally increase robot balance (Ude et al., 2004, Yamaguchi et al., 1999). From another side, integrating dynamic model into optimization procedure may provide additional tool for trajectory optimization. It may lead to faster robot movements in the case when joint acceleration will be induced not only because of actuation forces, but also by dynamic forces. However, this approach essentially complicates computations and may be hardly implemented for robot control through joint angles instead of demanded force level control. Besides, swing leg does not contribute a lot in robot dynamics since it does not effect robot body motion, which mostly defining robot stability. In contrast, it is a supporting leg (which is not considered in this work) that mainly defines CoM trajectory and, consequently, robot stability. From that point of view supporting leg trajectory could be unambiguously determined from stability condition while swing leg coordinates are redundant variables that might be optimised while step trajectory planning is proposed in this work. So, the suggested in this paper approach is a trade-off between a model complexity and utilization of robot total capacities. In practice, to avoid unpredictable robot behaviour, it is reasonable not to use upper velocity/acceleration boundaries in the optimization procedure since they may be higher in real model because of a presence of dynamic forces and errors in the model parameters.

The most essential limitation of the provided in our paper results is related to kinematic constraints induced to a hip location. It was strictly assumed that the hip height remains the same along the trajectory, while it is obvious that the best robot speed will be achieved when the height varies along the trajectory. In our approach, we separate swing and supporting leg movements and consider only a swing leg trajectory. Since a swing leg travels longer distances in walking, its joints should apply higher speeds and accelerations. Therefore, optimality due to kinematic limits is more important for a swing leg. We consider swing leg movement in coordinate system of a hip where the hip is fixed. Another direction for enhancing optimization efficiency is considering hip speed as an additional optimization parameter, which may vary from one via point to another. Providing reasonable solutions of the above-mentioned drawbacks and their integration into the optimization algorithm will apparently lead to robot speed increase. These issues will be addressed in details in our future work.

8 CONCLUSIONS

In this paper we considered a problem of searching optimal primitives for a swing leg trajectory, which minimizes its travel time under joint angular velocity and acceleration limits. Effective dynamic programming approach was used to obtain a desired optimal trajectory. It is shown that the obtained optimal trajectory enables to decrease step time, i.e. to increase robot speed compared to trajectories, which had been traditionally used to control a swing leg motion in bipedal robot locomotion. It is also shown that the presented trajectory optimization approach essentially increases speed of humanoid robot AR-601M. The developed approach will be further applied for optimization of a swing leg trajectory with regard to a support leg and joint range limits. Next, a set of optimal walking primitives will be extended to the case of walking on the surface of variable height (stairs and incline) as well as curved paths that will bypass insurmountable obstacles and walking in any direction. Besides, walking primitives with variable hip height and hip speed will be considered as an objective for further optimization algorithm enhancement.

ACKNOWLEDGEMENTS

This research has been supported by Russian Ministry of Education and Science as a part of Scientific and Technological Research and Development Program of Russian Federation for 2014-2020 years (research grant ID RFMEFI60914X0004) and by Android Technics company, the industrial partner of the research.

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