INSTANTANEOUS ON-LINE MODIFICATION OF BIPED WALK COMPOSED FROM RECONFIGURABLE ADAPTIVE MOTION PRIMITIVES

by

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The paper presents development and potentials of a novel methodology for biped walk synthesis based on motion primitives. This approach is convenient for on-line modification of walk in unstructured and immediate environment of humans. The modification is specified just by changing the overall walking parameters (walking speed, direction, step length, ...) and the system automatically adapts walk realization (legs motion) to comply with new requirements. Modifications may be required anytime, even during motion realization. Simulation results illustrate the proposed approach.

Key words: *biped locomotion, reconfigurable adaptive motion primitives, unstructured and dynamic environment, motion modification*

Introduction

In view of the fact that future robots will act in the immediate environment of humans such as offices, apartments, and hospitals, *the living and working coexistence* of humans and robots is inevitable. The fact that the robots will share the common space with humans imposes a requirement to act with an efficiency that is comparable to that of man. Efficient actions are inconceivable without an efficient motion. Bearing in mind that the environment consisting of different objects (chairs, tables, furniture, *etc.*) or having uneven walking surfaces (thresholds, stairs, *etc.*) is mainly adjusted to the humans and it cannot be expected that it will be essentially modified to suit the robot's need. Thus, it can be concluded that two-legged motion cannot be avoided.

Two-legged locomotion comprises basically two issues: gait synthesis (generation) and walk realization. The gait synthesis means that motion of all joints (not just legs) have to be determined in such a manner that locomotion system is performing desired walk (in the desired direction, speed, gait type, …) and that system is able to resist disturbances and perform walk in a reliable manner. Since the disturbances are always present during the gait, the compensation of their effects and maintenance of dynamic balance (prevention of the fall), is of crucial importance. Disturbances may be very different, both in respect of the type and the effect on locomotion system. Each of them should be compensated in a different way. In this paper, it is unlikely to pay particular attention to the issue of disturbance compensation. Interested readers can find more details in [1] about the compensation of small and in [2] about the compensation of large disturbances.

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The environment in which robot have to operate is unstructured and dynamic. Therefore, walking arise to be a particularly intriguing and delicate task. In case robot has to operate in such environment the basic problem arises from the fact that it is impossible to prepare program motion in advance. Instead, due to unstructured and dynamic nature of the environment, the decision about motion depends on the situation in the environment at the moment. It may even happen that situation in environment suddenly changes while the robot is executing the previous decision. This requires a quick reaction from the system. Modifications in movement realization should be applied almost instantly. Their realization appears to be a basic and most challenging requirement imposed to gait generation, along with the need of permanent preservation of dynamic balance. This paper deals with the description of an approach which enables it.

Taking into consideration all requirements mentioned a novel methodology was developed that enables synthesis of online modifiable walk based on reconfigurable adaptive motion primitives (RAMP) defined in a new and original way. Together with motion synthesis, the cascade control system for preserving dynamic balance while ensuring the motion execution is developed. This paper presents and describes the advantages and possibilities of the usage of this novel methodology on the example of biped walking in unstructured environments. Simulation results show that with the use of RAMP, biped walk can be adapted online to comply instantly at any moment. Thus, walking can be adjusted to changing environment by adapting RAMP parameters permanently, according to the position and motion of objects in robot’s surrounding. As input, the control system requires only simple and general walking parameters such as walk speed, direction, step length, *etc.*, while system should ensure automatic execution of appropriate motion. This offers an intuitive interface for integration of this system with higher level path planning algorithms.

Background and previous work

Walk of humanoids is mainly compared with the walk of humans. However, one should be aware of the fact that humans have been training and gaining their walking skills over a huge period of time, i.e. since the toddler years. After years of training, humans acquire superior walking skills, so they can focus on simultaneous execution of multiple tasks, like simultaneous talking, gesturing, manipulating objects, while walking without paying attention to the motion of legs and permanently preserving dynamic balance. Thus, we can conclude that humans are very efficient in walking even in unstructured environments and even in the case they are occupied with different tasks simultaneously [3].

Developing humanoid robots with such skills is, however, a challenging and extremely complex task. The first mathematical model for artificial biped walking was presented in [4], more than forty years ago. The well-known concept of zero moment point (ZMP) [5], which can be used as an indicator of dynamic balance and clearly suggests how to preserve a dynamic balance of bipeds, is inevitable in the realization of a walk for humanoids. It also should be mentioned that at the same time the ZMP was used as an important part of the first algorithm suggesting a way gait synthesis can be done – semi-inverse method*. How-

* Semi-inverse method suggested that problem of extremely large number of joints to be properly driven and coordinated can be solved in the following way: motion of the legs can be copied from humans, motion of the arms and neck predefined, while motion of the waist should be calculated in such a way that ZMP is at predefined position within support polygon defined by footprints. In addition, solution should fulfil repeatability conditions (angles and angular velocities of all joints at beginning and at the end of one step should coincide).

ever, this method was unsuitable for situations where decisions about the walk performance should be made quickly and almost instantly synthesized and completed. For online walk synthesis, advanced humanoids are mostly applying the well known Kajita's pattern generator with ZMP preview controller [6]. For the implementations of this method [7, 8], it is required to define the position of footprints the robots' feet should reach. In order to preserve a dynamic balance of the system, it is necessary to assign a reference trajectory for the ZMP, based on the planned feet placement and motion of the centre of mass. The motion of the rest of the system is then calculated to satisfy it.

The approach we propose for synthesis and realization of walk based on RAMP is introduced in [9] in details and just briefly presented here. The focus in this paper will be on pointing out the advantages and easiness of using RAMP and demonstration of applicability for walking in an unstructured and dynamic environment where sudden changes and modifications (even of the movements whose realization already started) cannot be avoided. The inspiration for using RAMP comes from neurological studies [10, 11] where it has been shown that electrical microstimulation of the spinal cord evokes synergistic motion of multiple joints toward an equilibrium point in space. The collections of the motions correspond to a well-structured spatial pattern (vector field) that was convergent and characterized by a single equilibrium point. In [11] there are important findings that point out that organization of spinal motor systems in the frog spinal cord is probably modular. Experiments show that simultaneous stimulation to two different sites in the spinal cord causes the motor output that is a simple combination of separate motor outputs. Based on these observations it was proposed that complex movements might be produced by the flexible combination of a small number of spinal - generated motor patterns. In a similar context, the proposed primitives are defined as simple parameterized movements which are realized by simultaneous and synchronized motions of a number of joints. By combining different primitives, complex motion can be obtained (*i. e.* walking), without having reference joint trajectories that are prescribed in advance.

Although the application of primitives for movement generation is hardly an entirely new approach, different authors define primitives in different ways. In [12] there is a library in which each primitive represents one step. Based on the preset requirements and the current state of the robot, a new step which corresponds to the requirements is selected from the library. In [13], the leg motion primitives are obtained by segmenting and modifying the movements recorded from man. In [14, 15], the author introduced the notion of dynamic movement primitives (DMP), a framework for execution of robotic trajectories which models attractor behaviours of nonlinear dynamical systems with the statistical learning techniques on top. In [16] authors further expanded the DMP framework by enabling interaction of robot with objects in its close environment.

Composing the walk from RAMP

The RAMP methodology is quite different from any other walk synthesis algorithm. Placement of feet on the ground and all other walking characteristics are not strictly predefined in advance, but are rather a consequence of mutual influence of the set of overall *soft*[*] walk parameters applied (desired walking speed, step length, direction, *etc.*). To enable that

[*] Soft parameters means that it is not strictly defined that the walk should comply with actual parameters, but it will try to achieve them only if the situation allows (*i. e.* dynamic balance is not endangered), and if the constraints of the system as a whole allow realization of desired motion.

change of RAMP execution can modify walk in desired way the relationship is established between the desired overall parameters of walk and the corresponding parameters of each RAMP. If the overall parameter has been suddenly changed (for example, walking direction) transfer from current direction to a new one will be gradual. The shape of the walk, *i.e.* joint trajectories, should not be repeated with high precision. Even with straight walking on flat surfaces, each step in the process can be slightly different from others. The start of execution of each RAMP is unlikely time dependent, but rather depends on the condition that a robot is in such pose that execution of the RAMP is feasible. An important prerequisite for all RAMP is that synthesized motion has to be online modifiable in very strict form. This means that when any of the overall parameters of the walk is changed, it does not cause expensive computation, but the parameters of RAMP are changed and the resulting motion gradually complies with new parameters.

By careful analysis of motion and movements, it can be proved that any complex motion (including walking) consists of an appropriate sequence of simple parameterized movements* – RAMP. Let us underline that RAMP has been executed without calculating joint reference trajectories in advance. Each RAMP is defined as a simple parameterized motion that involves several joints, for example, joints of one leg. Based on the parameters of the RAMP, the goal position of the attached coordinate frame has to be defined as well as the shape of the trajectory from the current position. Any approach that will lead to a simultaneous motion of multiple joints with modifiable parameters can be used as a technique for executing RAMP.

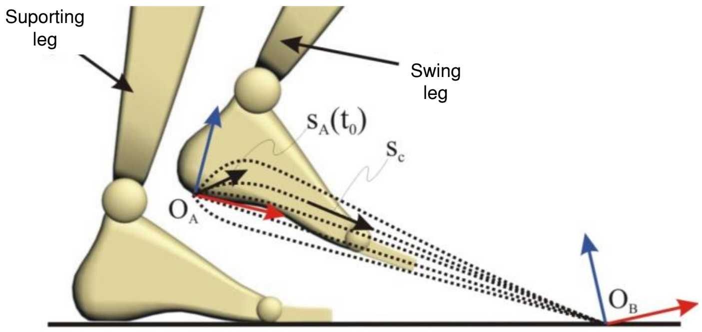

Figure 1. Legs of robot at the beginning of the leg stretching execution and the family of possible trajectories of co-ordinate frame O_A on its path to reach and coincide with co-ordinate frame O_B

It is important to note that smooth continuation of tied subsequent primitives is required. In the case of analytical form (which will be used throughout the rest of the paper), the smoothness is achieved by considering the current velocity of the attached coordinate frame. Leg stretching is one of the RAMP that will be used for walking synthesis. In the example of leg stretching the procedure for calculating joint motion will be illustrated. Figure 1 shows the time instant when the robot, in a dynamically balanced posture, completes a leg bending RAMP. The movement should be smoothly continued by leg stretching. The vector $\vec{r}_A$ defines the instantaneous position of the co-ordinate frame O_A (attached to the heel of the swinging leg) while the $\vec{r}_B$ represents its target position, *i.e.* the position of coordinate frame O_B to which O_A is to be brought. The position and orientation of coordinate frame O_B is determined from the parameters of the RAMP. The velocity of co-ordinate frame O_A, denoted by S_A, depends on the in-

* Such simple movements are comprising more joints simultaneously (for example leg bending, leg stretching, …) and we named them after motion primitives. Movement of each primitive should fulfil certain "goal". For leg bending "goal" is to deploy foot from ground to enable easy and fast leg transfer from back to front position. Deployment is monitored by position of coordinate system attached to the foot.

tensity and direction of the velocity $s_A^0 = s_A(t_{p0})$ at the starting moment. The desired velocity $s_A(t_i)$ is calculated as:

$$s_A(t_i) = (1 - b(t_i)) \cdot s_A^0 + b(t_i) \cdot \begin{bmatrix} v_{int} \cdot p_e^{ort} \\ w_{int} \cdot o_e^{ort} \end{bmatrix} \tag{1}$$

where p_e^{ort} and o_e^{ort} are the orts of the $p_e = p_B - p_A$ and $o_e = o_B - o_A$ *i. e.* the position and orientation between r_A and r_B. In eq. (1), the coefficient *b* changes during the prescribed time interval from 0 to 1. This ensures a gradual change of the velocity s_A from the initial value s_A^0 to the value that will lead the frame O_A to the target position O_B. Intensities of the linear and angular velocities v_{int} and ω_{int} are dependent on the cruising speeds v_c and ω_c, which are set by the RAMP parameters. To ensure a gradual stopping of the leg, the intensities of the velocities v_{int} and ω_{int} have to be reduced when O_A comes sufficiently close to the target. Having thus determined $s_A(t_i)$, and using inverse kinematics, the desired joint angular velocities can be calculated.

To synthesize basic walk (as the basic walk is considered walking on a flat surface with moderate speed), first, the regular walk is analyzed and decomposed in such a way as to enable RAMP execution with respect to the selected technique. Let us suppose that the motion begins from the posture in which the robot is standing still in the double-support phase (fig. 2).

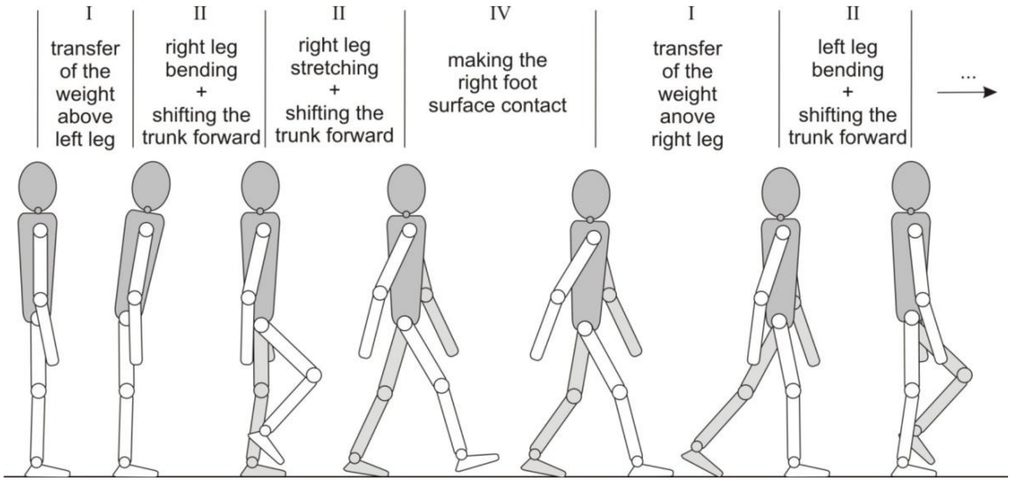

Figure 2. Decomposition of the walk into the phases that can be realized by RAMP

During the first phase, the robot transfers its weight onto the supporting leg. In the case considered this is the left leg. This action takes place either if the robot is standing still and motion has just started or the system is already in motion, as well as in the double support phase when the load has to be transferred to another leg. During the second phase, the right leg deploys from the ground (leg bending RAMP) and the whole system inclines forward. In the third phase, the swing leg stretches (leg stretching RAMP), and it is brought in front of the body, while the robot is inclining simultaneously forward, in order for the system to be prepared to pass to the forthcoming double-support phase. In the fourth phase, the double-support phase begins by the foot landing on the ground to make a surface contact and the

RAMP for ensuring foot surface contact is executed. The ending of the fourth phase is followed by the phases which are identical to the first four. The only difference is that the RAMP is now realized by the other leg. These phases are repeated cyclically as long as it is necessary for the robot to walk.

For gait synthesis, the decomposed phases are described, where five RAMP realized by the legs are introduced along with one realized by the trunk and one by the arms. The RAMP realized by the legs in the single-support phase is:
– bending of the leg in the swing phase,
– stretching of the leg in the swing phase, and
– inclining the robot forward.

The RAMP realized during the double-support phase is:
– making the foot surface contact after the heel strike and
– transferring the body weight onto the subsequent supporting leg.

The RAMP realized by the trunk and arms is:
– maintenance of the trunk upright posture and
– arms swinging during the walking.

While the robot is walking the following requirements should be fulfilled simultaneously: legs should move in such a way as to ensure motion of robot along the selected path, while the motion of the whole body has to move in a synergetic manner to ensure dynamic balance. To fulfil these requirements the cascade control system is developed, consisting of four blocks: path planning, configuring the RAMP, dynamic balance controller and joint motion controller (fig. 3).

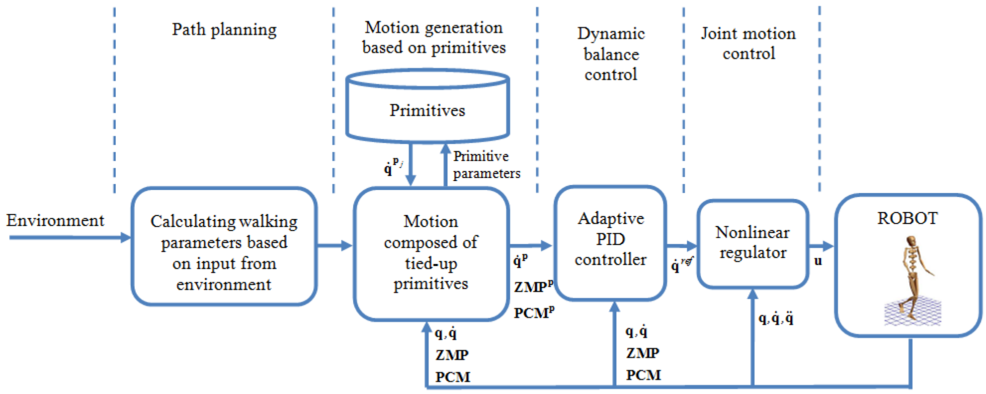

Figure 3. Cascade control system consisting of path planning block, block for combining RAMP, dynamic balance controller and joint motion controller

The first block is responsible for calculating walking parameters based on the input from the environment. The second block is accepting the desired parameters of walk and defines joint angular velocities for the tied-up RAMP. Since, RAMP fails to take into account the dynamic balance of the system, the third block is introduced for correcting desired joint velocities with respect to the current position of ZMP and projection of the whole system center of mass. Finally, the fourth block is responsible for driving the actuators in the joints. A non-linear regulator is used for this purpose as a combination of feedback linearization, sliding mode control and disturbance estimator [9]. Based on the input from the environment, first block needs only to determine overall motion characteristics: walk speed W_{Speed}, the height to which the foot is lifted during the swing phase W_{Height}, step length W_{Length} and walking direction W_{Dir}. Overall walk parameters can be changed at any time causing an immediate and automatic change of parameters of the primitives. Therefore, the relationship between the primitive parameters and the preset overall parameters of the walk has been established. Stick diagram and position of ZMP (red crosses) and PCM (blue circles) with respect to the placement of the footprints for the walk realized with the overall walking parameters being set as: $W_{\mathrm{Speed}} = 1$, $W_{\mathrm{Height}} = 1$, $W_{\mathrm{Length}} = 1$ and $W_{\mathrm{Dir}} = 0$ are shown in fig. 4. Walk realized with these parameters is denoted as basic (base) walk.

The presented methodology for synthesizing and realizing walk is shown to be robust and adaptable to an unknown terrain configuration [17]. It was shown that robot is able to walk against an uneven terrain configuration unknown to the robot.

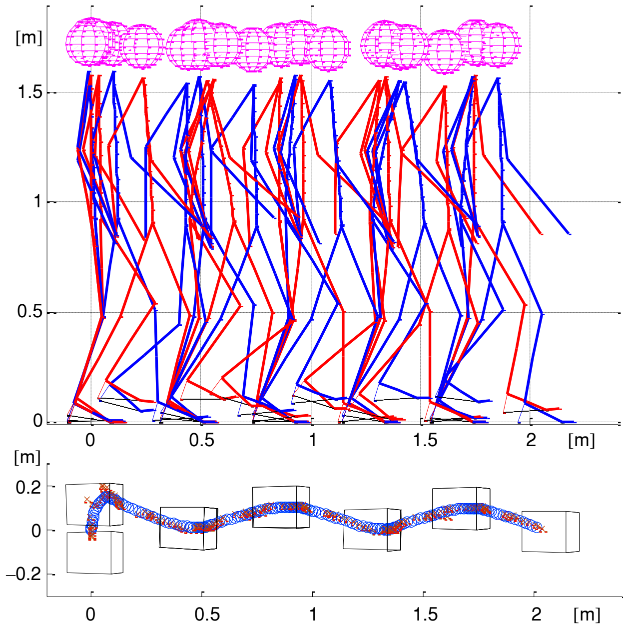

Figure 4. Stick diagram (top), footprints and position of ZMP and PCM (bottom) for the base walk

Instantaneous modification of overall parameters of walk

The following simulation examples show the possibility to modify the overall parameters of walk instantaneously at different time instants and its comparison with basic walk. In fig. 5. stick diagrams and trajectories of ZMP and PCM are shown in the case when W_{Height} is set to 2.5 (foot height during swing phase has been increased) at a random time instance soon after the execution of the leg bending RAMP started. Black and green lines are introduced in the same figure to show the difference between the trajectories of the left heel for basic and modified (increased heel height during swing phase) walk. There are also shown ZMP and PCM trajectories for the base (red crosses and blue circles) and modified walk (green crosses and cyan circles). It can be concluded that the introduced modification of walking parameter insignificantly influences overall dynamic balance because dynamic balance control is keeping the robot all the time well balanced.

Figure 6. illustrates same modification of walk as in the previous example but time instant when the modification was introduced was different and selected to be close to the end of the execution of the leg bending RAMP. This can be easily visible by comparison of green lines in figs. 5 and 6. In fig. 6. it can be also visible that the robot is more abruptly changing the trajectory of the heel. However, it can be seen that joint angle trajectories in both cases are similarly modified compared to base walk, and it can be concluded that also, in this case, robot successfully modified its walk.

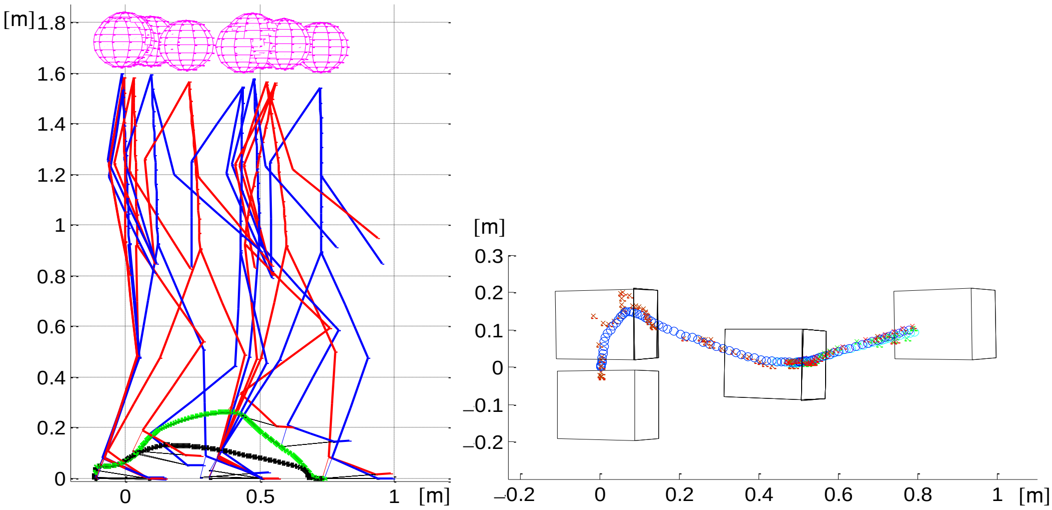

Figure 5. Stick diagram (left), footprints and the position of ZMP and PCM (right) for the case when the W_{Height} is set randomly soon after the execution of the leg bending RAMP of the left leg started. Green and black thick line on stick diagram represents the trajectory of left heel for modified and base walk, respectively

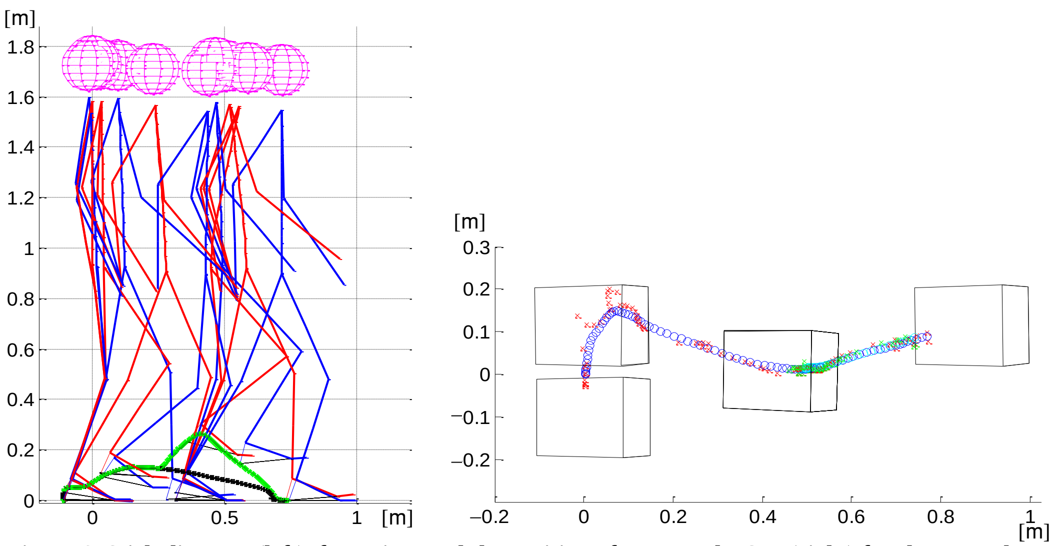

Figure 6. Stick diagram (left), footprints and the position of ZMP and PCM (right) for the case when the W_{Height} = 2.5 is set randomly close to the end of the left leg bending. Green and black thick line on stick diagram represents the trajectory of left heel for modified and base walk, respectively

Illustrations of another modification are shown in figs. 7 and 8 – an increase of the step length starting at different time instants. In the first case, modification of step length has been introduced just after the execution of leg bending RAMP started. In the second case, modification has been introduced just before the ending of leg stretching, when the heel of the swing leg was close to the ground. Even in that case, remaining time was enough to realize longer stride before entering the double support phase, *i.e.* before the left heel hit the ground. In both cases W_{Length} was set to 1.5.

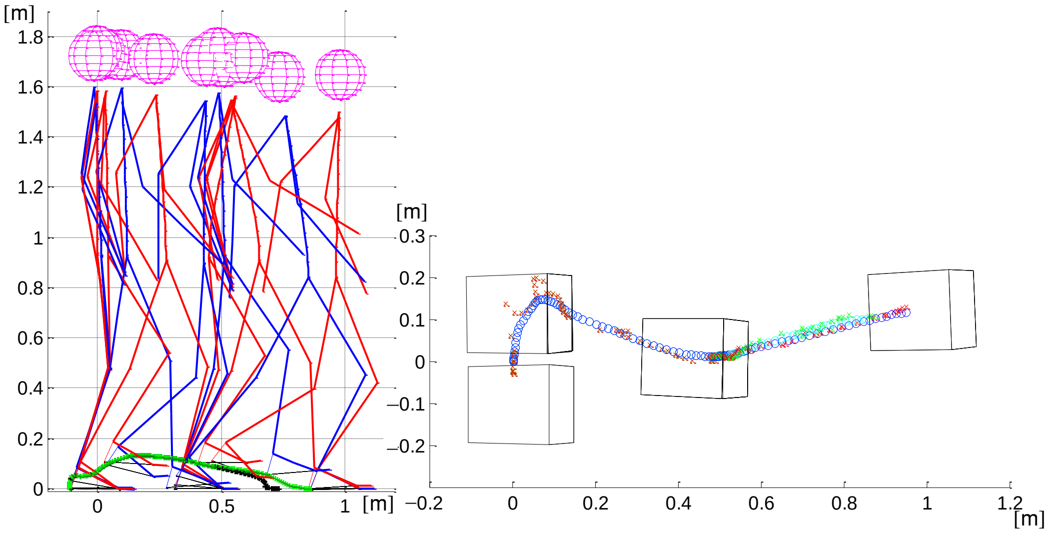

Figure 7. Stick diagram (left), footprints and position of ZMP and PCM (right) for the case when the W_{Length} = 1.4 is set just after leg stretching of the left leg started. Green and black thick line on stick diagram represents the trajectories of left heel for modified and base walk, respectively

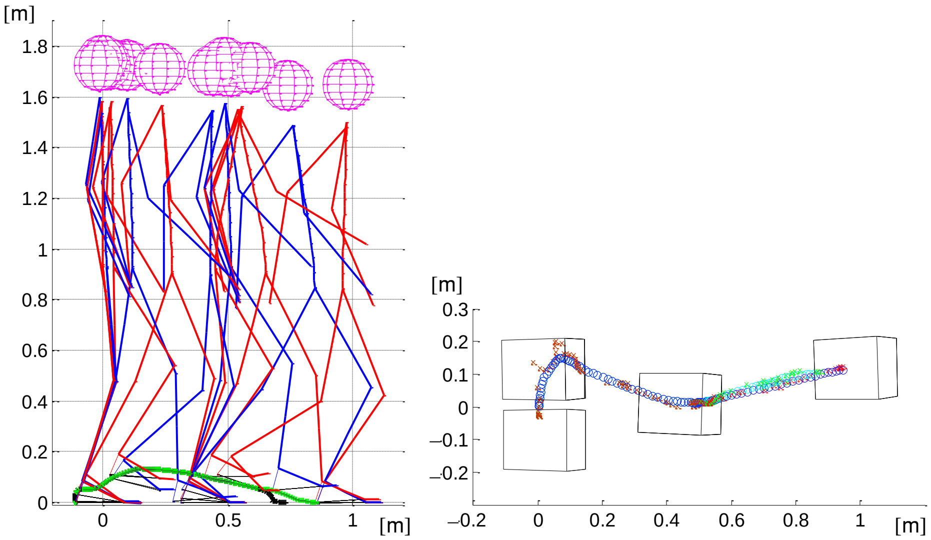

Figure 8. Stick diagram (left), footprints and position of ZMP and PCM (right) for the case when the W_{Length} = 1.4 is set randomly close to the end of the left leg stretching RAMP. Green and black thick line on stick diagram represents the trajectory of left heel for modified and base walk, respectively

Change of direction has been illustrated in the last simulation example (fig. 9.). At the arbitrarily selected time instant (again, just after starting the execution of leg stretching RAMP) modification has been introduced. The walking direction was changed for 10^{o} with respect of the initial direction. In fig. 9. the dissent of ZMP and PCM between basic and modified walk (colours are the same as before) are visible, indicating different directions of the walking path.

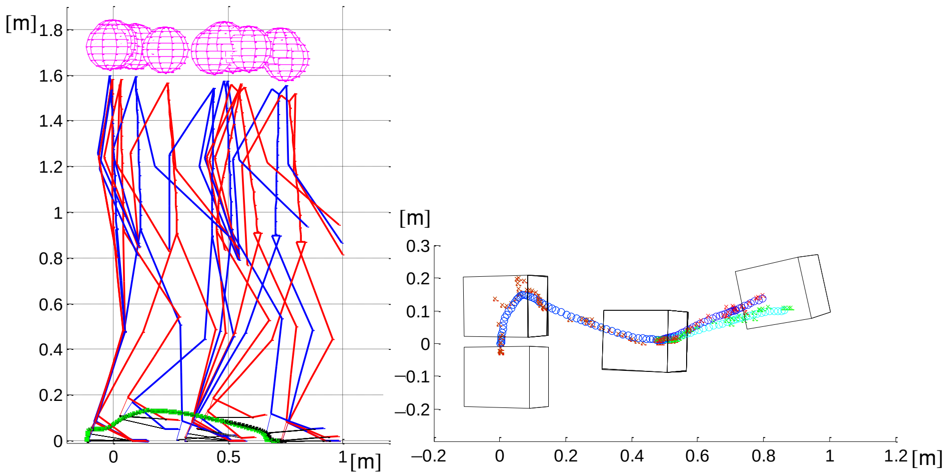

Figure 9. Stick diagram (left), footprints and position of ZMP and PCM (right) for the case when the W_{Dir} = 10° is set randomly just after the leg stretching of the left leg started. Green and black thick line on stick diagram represents the trajectory of left heel for modified and base walk, respectively

Conclusion

Contemporary robots are intended for using in the immediate environment of humans which is unstructured and dynamic. The consequence of such environment is that it is impossible to prepare programs for robot motion in advance. Robot motion has to be synthesized and realized according to the situation at this particular moment when decision about change is brought. It may even happen that the motion whose realization started has to be modified. Walking is one of the most important and complex motion activity which requires locomotion system to be permanently *on its feet i.e.* to be dynamically balanced. Novel methodology for biped walk synthesis and realization based on RAMP was presented in this paper. The presented simulation results illustrate the convenience for online modification of walking parameters in order to comply with the current situation in the environment. The results highlighted how the online modification of biped walk can be achieved without any need for calculating reference of joint trajectories each time when the situation has been changed in the surrounding environment.

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