Biped Walking and Stairs Climbing using Reconfigurable Adaptive Motion Primitives

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***Abstract*— Humans can reliably walk in dynamic and unstructured environments, simultaneously handle stairs and obstacles, as well as the transition from one gait to another. Despite the outstanding progress in the last decades, today's robots are still far from attaining that level of performance.**

This paper presents a new way of walk and stair climbing realization with a smooth transition between two types of gait. The gaits are composed of Reconfigurable Adaptive Motion Primitives (RAMPs), which serves as building blocks for any walking pattern. A human locomotion experiment is conducted to better understand how human approaches and positions the foot in front of the stairs with respect to the overall walk characteristics. These findings are used to compare the results of a simulation experiment with humanoid robot performing same locomotion as the human subject. It is shown that the robot's path or gait shape can be modified by the set of overall gait parameters that can be changed at any time instance. The robot can approach stairs with a variable number of half-steps, switch smoothly to stair climbing, and back to walking on flat surface, and modify walking speed and direction on-line as humans can do.

I. Introduction

The emphasis of research in biped locomotion has moved toward enabling robots to deal with the real life environment, like walking on uneven terrain, negotiating doors, climbing stairs and ladders [1], [2], [3]. A large motivation arose from the 2011 Fukushima disaster and the DARPA Robotics Challenge. As a result, numerous robots have improved performances and are now able to overcome different types of obstacles while simultaneously accomplishing complex manipulation tasks.

Even though the research progress has been remarkable, the capacity of such robots, to smoothly switches between different gaits is still modest. If we expect robots to move and operate in human-centric environments, the flexibility of the robots to modify their motion instantly has to be as close as possible to those of humans. Simultaneously, the control system has to successfully handle any type of gait as well as to compensate for the always present disturbances and prevent the robot from falling.

The term "motion primitives" has been defined in different ways by different authors. In papers [4], [5], Schaal defined dynamic movement primitives as units of action, formalized as stable nonlinear attractors. Authors in [6], [7] proposed a modular approach to movement generation based on the motor primitives, with a simple trajectory generator for discrete and rhythmic movements. In [8] is introduced a trajectory generation method for humanoid robots based on kinematic motion primitives (kMPs) derived from recorded human's trajectories. They showed that from a small set of periodic and discrete movements, it is possible to reconstruct the necessary joint trajectories to obtain the desired motion.

In this paper, the motor control system introduced in [9] is successfully applied for stair ascending. It enables the robot to smoothly (without any stopping) transfer the gait from walking to climbing stairs and vice versa. First, in Section II is given the overview of relevant previous work with the emphasis on specificities of climbing stairs. In Section III, RAMP based motor control system for walking and climbing the stairs is presented. Afterward, in Section IV motion capture (MOCAP) recordings of a human subject when approaching and climbing stairs is analyzed. Based on the analysis, in Section V the simulation results are presented that show the ability of a robot to adapt its walking to approach the stairs similarly as humans do and to transfer from walking on flat ground to climbing stairs without the need to precisely position its body in front of the stairs.

II. Related Work

Biomechanical analyses and the data obtained from motion capture systems provide a valuable insight into the behaviors during human locomotion. In [10] kinematic strategies of newly walking toddlers and adults were compared for stepping over different support surfaces, including stair ascent and descent. The results, obtained from motion analysis system, have shown that the adult subjects, unlikely the newly walking toddlers, never stepped on the edges of the staircase but always on the tread, which supports the idea that adult humans make anticipatory locomotor adjustments and appropriate changes in the walking patterns. To successfully approach stairs, and transit to stair climbing humans are relying on vision system. Humans do not measure the distance from the stairs, nor the height and the depth of each stair. The position of the feet are not determined in advance but are on-line adapted based on the input from the vision system.

So far, there are several biped robots that have successfully accomplished the stair climbing and descending task.

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Applied approaches assume quite precise knowledge about the shape, size and location of the stairs. Authors in [11] used the data captured by a stereo vision system. The stairs were extracted from the segmented plans and fed to the controller of QRIO robot. In [12], a fully-integrated on-line perception-planning-execution system was combined with a footstep planner and a controller capable of adjusting the height of the swing leg, which allowed HRP-2 robot to localize, approach and climb stairs. The first approach for autonomous climbing of humanoid robot on spiral staircases was presented in [13], where a 2D laser range finder and monocular camera were implemented on a NAO robot.

An algorithm for gait planning and the compliant controller for a biped robot climbing stairs was proposed in [14]. The desired Zero Moment Point (ZMP) was derived from the iterative optimal algorithm, providing sufficient stability margin to implement energy saving. The controller with variable impedance and force sensing was proposed to cope with environmental disturbances. An issue concerning the problem that arises from the fact that the robot feet are placed on different heights was addressed in [15]. Recently, several research papers have been published on autonomous planning and control framework for humanoid robots climbing a ladder- and stair-like structures. In [1], an off-line planner of the finite state machine is presented, based on a position of contacts needed to climb the ladders. The approach presented in [2] consists of a multi-limbed locomotion planner combined with a compliance controller that compensates for errors from sensing, calibration and execution.

The existing approaches for generation and realization of biped locomotion have the following shortcomings: (i) they do not offer the flexibility of changing the motion parameters on-line and, (ii) they do not offer a smooth transition between different gait types such as walking and stair ascending.

In [9] control system for walking on a flat horizontal surface with the ability to modify on-line parameters of the walk is presented. The motion synthesized by RAMPs was further improved in [16] by introducing the gradient descent algorithm for learning the parameters of combined RAMPs to achieve more efficient humanoid walk through better synchronization of the RAMPs that are executed in parallel. The experiments in [17] showed the robustness of the motor controller by compensating the disturbance that arises from the uneven terrain configuration.

In this paper, a system for gait synthesis and control for climbing the stairs is presented. The proposed control system does not require precise information about the height and the depth of the stairs. Both control systems (for walking and stair climbing) are based on the use of RAMPs and it will be shown how the gait planner switches between two types of gait. Results of the simulation experiment show the ability of the robot to adjust its step length while approaching the stairs without the need to precisely position its foot in front of the first stair, and the robustness of the control system with respect to the information about the geometry of the stairs.

III. RAMP based Motor Control System for Walking and Climbing Stairs

While the robot is walking, the legs should move in such a way as to ensure motion of robot along the selected path, whereas the whole body has to move in a synergetic manner to ensure dynamic balance. To fulfill these requirements the cascade control system is proposed in [9], consisting of: (i) block for combining the RAMPs; (ii) dynamic balance controller and; (iii) joint motion controller (Fig. 1).

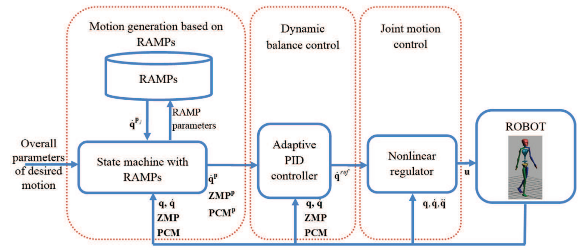

Fig. 1. Block diagram of the robot control for the realization of the motion synthesized using RAMPs

The first block is a kinematic controller in velocity space that ensures the smoothness of the resulting motion. This block is composed of RAMP functions which are combined together in state machines (one state machine for one gait type). An example of RAMP function for calculating desired heel velocity during leg stretching is given by the following equation:

$$\mathbf{s}_A\left(t_i\right) = \left(1 - b\left(t_i\right)\right) \cdot \mathbf{s}_A^0 + b\left(t_i\right) \cdot \begin{matrix} v_{int} \cdot \mathbf{p}_e^{ort} \\ \omega_{int} \cdot \mathbf{o}_e^{ort} \end{matrix} \tag{1}$$

where $\mathbf{p}_e^{ort}$ and $\mathbf{o}_e^{ort}$ are the unit vectors of the $\mathbf{p}_e = \mathbf{p}_B - \mathbf{p}_A$ and $\mathbf{o}_e = \mathbf{o}_B - \mathbf{o}_A$ i.e. the position and orientation between $r_{\mathbf{A}}$ and $r_{\mathbf{B}}$ (vector $\mathbf{r}_A$ defines the instantaneous position of the heel of the swinging leg while the $\mathbf{r}_B$ represents its target position). In eq. 1, the coefficient b changes from 0 to 1 during the prescribed time interval, to ensure a gradual change of the velocity $\mathbf{s}_A$ from the initial value $\mathbf{s}_A^0$ to the value that will lead the heel to the target position. Intensities of the linear and angular velocities v_{int} and ω_{int} are dependent on the biped cruising speeds v_c and ω_c, which are set by the primitive parameters. To ensure a gradual stopping of the leg, the intensities of the velocities v_{int} and ω_{int} have to be reduced when heel comes sufficiently close to the target. Having thus determined $\mathbf{s}_A\left(t_i\right)$, and using inverse kinematics, the desired joint angular velocities of one leg can be calculated.

The first block does not consider the dynamic balance of the system. While biped is performing a gait, due to ever present disturbances, a dynamic balance has to be preserved simultaneously. When the robot is walking on a flat surface the motion of the robot is constantly adjusted to keep the ZMP inside the support area [18], [19]. For stair ascending, the different cases arose. The first one is the case when the robot is in single support phase during which the robot's foot establishes surface contact with the ground. For this case, the notion of the ZMP holds, and for preserving dynamic balance a controller similar to one introduced in [20] is used. In the second case, the robot is establishing a contact with both of its feet on different, but parallel planes (phases IV and I on Fig. 2 b). In this case is not possible to calculate ZMP in a traditional way. The dynamic balance controller is calculating separately for both feet as well as a resulting center of pressure (CoP) and total ground reaction force (GRF). The desired joint velocities are corrected in such a way to keep the CoP as close as possible to the desired position.

Finally, the third block is responsible for the realization of the reference motion on the joints level. For that a non-linear controller is used that integrates feedback linearization, sliding mode control and disturbance estimator.

For synthesizing the walk, we decomposed it into four phases as shown in Fig. 2 a):

- phase I: transferring the weight onto the supporting leg,
- phase II: a simultaneous realization of leg bending and forward inclination of the supporting leg,
- phase III: a simultaneous realization of leg stretching and forward inclination of the supporting leg,
- phase IV: making the foot surface contact.

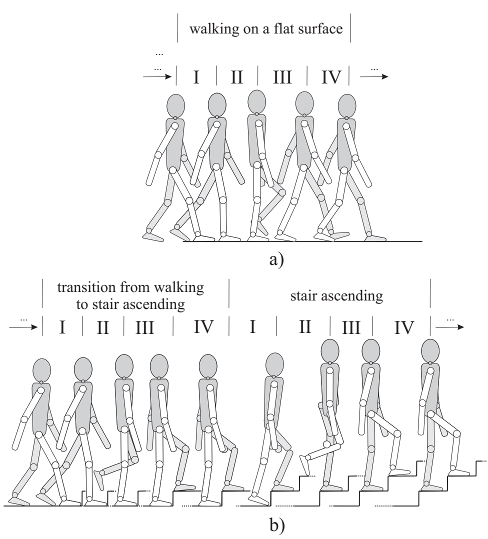

Fig. 2. Decomposition of the a) walk and b)stair ascending into the phases.

Based on the decomposition of walking the following RAMPs are defined: leg bending, leg stretching, transferring the weight onto the supporting leg, forward inclination, making the foot surface contact, keeping the trunk upright and arms swinging. Each RAMP is defined as a function that calculates desired joint angular velocities of the associated joints as shown in eq. 1 for leg stretching RAMP. Through each phase, several RAMPs can be executed in parallel, and after one phase is over[1], the next phase is starting with an ensured smooth change in joint velocities.

In order to perform overall desired motion[2] it is necessary to introduce the overall parameters of the gait and to establish the relationship with the parameters of the RAMPs. In the case of walking, the following set of overall parameters are introduced: walking speed, step length, walking direction and height of the leg during the swing phase.

Climbing the stairs has also been divided into the phases (2 b)). When the foot of front leg lands on a stair (start of the phases I on 2 b)), the body weight is transferred to the front leg (future supporting leg). This is the start of phase II. Once the body weight is transferred, the back foot is lifted off the ground and the leg bending in parallel with forward inclination starts. Clearly, leg bending is in a relationship with the height of the next stair in front of the robot. When the foot of a swing leg is brought to the desired position the leg stretching start (start of the phase III) and forward inclination is continued. The parameters for leg stretching depend on the height and depth of the next stair and climbing direction. After the heel comes in contact with the ground support, the leg stretching ends, and the movement for establishing foot surface contact starts (start of phase IV). Once the foot establishes surface contact the robot is ready to start with phase I. It is important to emphasize that the same phases with the same set of primitives are used as for walk on a flat surface (2 a)). Thus, this four phases cycle is repeated for as long as it is required for the robot to walk or climb stairs. The only difference between walk and climbing stairs is the different set of overall parameters and their relationship with RAMP parameters. For walking on the flat surface the overall parameters are: walking speed, walking direction, step length and height of the foot during swing phase. For climbing stairs, the parameters are: climbing speed, climbing direction, height and depth of the stair.

IV. Human Locomotion Experiment

The insight into how the humans are modifying its walk when approaching the stairs can be retrieved from the recorded human motion. For that purpose, we conceived and conducted an experiment in which a motion capture system is used to measure the position of the markers placed on the subject during walking and stair climbing. It is especially interesting to analyze how the humans are positioning the foot in front of the stairs with respect to the overall walk characteristics (i.e. step length).

The subject for this experiment was a healthy adult male. The recording was conducted using the Vicon Motion Capture system with eight cameras having 2MP resolution and the frame rate of 200Hz. The subject was outfitted with the marker placement that matches the Plug-in-Gait Model together with the Oxford Foot model (Fig. 3)[3]. For the purpose of this experiment, the subject was asked to stand at the location with the specific distance from the stairs (unknown to the subject), to approach them and to climb

[1]The condition to start with the execution of the next RAMP is being checked automatically. If the conditions are not met, the realization of RAMP will not occur, and the robot will stop its motion.

[2]The RAMP parameters are automatically adjusted to perform desired motion specified only by the overall parameters (speed, walk direction,...)

[3]The subject provided informed consent and the experiment was approved by ethical committee of the University of Novi Sad.

the staircases. The staircases had four stairs and each stair was 17cm high and a 35cm deep.

Fig. 3. Experimental setup:The subject with the marker placement and the stairs

During the experiment, a total of 30 different trials were recorded. For each trial, the subject was brought to the randomly selected starting position with his eyes closed. After that, the subject was asked to open his eyes and to climb stairs. Ten equidistant starting positions (with the spacing of 10.33cm) were selected. The closest one was at 123.0cm from the first stair, and the furthest was at 216.0cm. Trials with each of the 10 different starting positions were repeated three times. Table I gives the length of the half-steps when approaching the stairs together with the initial distance of the subject from the stairs.

From Table I it can be seen that for two different starting positions (i.e. starting positions 6 and 10) the number of half-steps while approaching the stairs is not always the same. For starting position 6, in one trial the subject realized two longer half-steps and in two trials three shorter half-steps. Similar, for starting position number 10, in one trial the subject realized three longer half-steps and in two trials four shorter half-steps. This means that there are some critical distances when the humans will randomly decide for less longer or more shorter steps. In the case when longer steps are realized, the distance of the foot from the stair is larger compared to the case when shorter steps are realized. The first half-step for the stair climbing is thus longer. This gives the conclusion that humans select and adapt step length in different ways. In some cases, the longer half-steps and in some the shorter half-steps are realized to approach stairs before transferring to climbing. When different number of half-steps are realized for the same distance from the first stair (group of trials 6 and 10), the deviation of each half-step length from the average value, as well as the remaining distance from stairs at the end of approaching phase, are as follows:

- trial: 6-1; deviations: 2.5cm, -1.5cm, -5.9cm;
  distance from stairs: 0.66cm;
- trial: 6-2: deviations: -2.3cm, -2.3cm, -7.7cm;
  distance from stairs: 8.00cm;
- trial: 6-3: deviations: 10.9cm, 7.9cm;
  distance from stairs: 36.5cm;

TABLE I

NUMBER AND THE LENGTH OF HALF-STEPS WHEN SUBJECT IS APPROACHING STAIRS FROM DIFFERENT DISTANCES

Trial	No. of trial	Distance to the stair [cm]	Length of the half-step[cm]			
			1st	2nd	3rd	4th
1-1	13	123.00	59.4	53.9	-	-
1-2	21	123.00	56.7	58.4	-	-
1-3	28	123.00	56.3	55.0	-	-
2-1	17	133.33	63.0	56.9	-	-
2-2	23	133.33	58.9	56.0	-	-
2-3	30	133.33	43.0	56.4	-	-
3-1	14	143.66	58.9	56.0	-	-
3-2	25	143.66	64.2	62.9	-	-
3-3	29	143.66	59.3	63.4	-	-
4-1	16	154.00	67.6	75.6	-	-
4-2	19	154.00	67.9	59.8	-	-
4-3	26	154.00	60.6	66.6	-	-
5-1	4	164.33	59.2	57.8	-	-
5-2	24	164.33	63.0	68.6	-	-
5-3	27	164.33	63.4	61.9	-	-
6-1	6	174.66	62.1	58.2	53.7	-
6-2	9	174.66	57.3	57.4	52.0	-
6-3	22	174.66	70.6	67.6	-	-
7-1	2	185.00	62.2	59.4	54.1	-
7-2	10	185.00	59.6	59.8	56.8	-
7-3	18	185.00	57.7	63.7	54.1	-
8-1	5	195.33	53.3	64.2	58.5	-
8-2	8	195.33	63.1	63.9	61.1	-
8-3	15	195.33	61.1	62.7	62.6	-
9-1	3	205.66	57.5	54.9	61.7	-
9-2	12	205.66	57.7	64.8	63.3	-
9-3	20	205.66	62.9	62.5	60.0	-
10-1	1	216.00	58.2	55.6	59.6	40.7
10-2	7	216.00	61.9	61.8	61.5	-
10-3	11	216.00	65.6	59.7	54.6	34.5

- trial: 10-1: deviations: -1.4cm, -4.1cm, 0.0cm, -18.9cm;
  distance from stairs: 1.9cm;
- trial: 10-2: deviations: 2.3cm, 2.2cm, 1.8cm;
  distance from stairs: 30.8cm;
- trial: 10-3: deviations: 6.0cm, 0.0cm, -5.1cm, -25.1cm;
  distance from stairs: 1.6cm;

The data show that the distance from the first stair was much longer ($>$ 30cm) when the subject realized less longer steps (trials 6-3 and 10-2), comparing to the case when more shorter steps are realized (maximum distance is less than 10cm and the average is 3.04cm). Additional specificity is related with trials 10-1 and 10-3 where the last half-step is significantly shorter from an average length, but in these cases, the foot was positioning much closer to the first stair with the distance less than 2cm. This analysis gives a conclusion that the humans not necessary position their foot precisely in front of the stairs, and if the steps are shorter, the foot will be placed closer to the first stair. It can be concluded that humans make a rough estimation of the distance from the stairs and choose between shorter or longer steps.

V. SIMULATION EXPERIMENTS AND RESULTS

In this section, the ability of motor control system presented in Section III to perform ascending stairs and to modify its gaits on-line while approaching stairs and during stair climbing will be shown. The same control system is

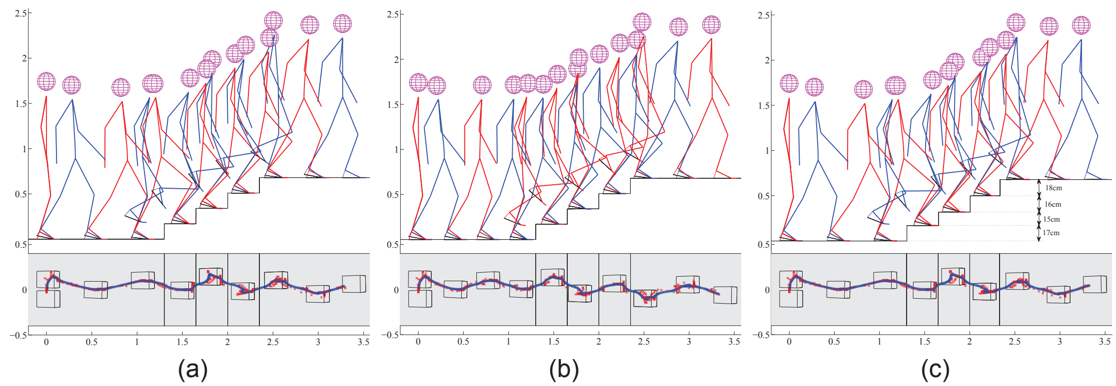

Fig. 4. Stick diagram of the robot, footprints, position of the CoP (red crosses) and PCM (blue stars) a) when approaching stairs with two longer half-steps; b) when approaching stairs with three shorter half-steps; c) with each stair having different dimensions.

used for both, walking and climbing stairs. For experimental validation, a simulation environment is used. The biped model used has four kinematic chains and 51 degrees of freedom. The height of the robot is 1.85m and the mass is 74.8kg. The contact between the foot and the ground is determined by six characteristic points (four contact points are at the corners of the foot body sole, and two are at the top corners of the toe segment). The foot was defined as a rigid body with a viscoelastic layer on the sole that was modeled as an isotropic Kelvin-Voigt material with stiffness set to $86kN/m$ and damping set to $1.1 \cdot 10^3$kNs/m). The complete model includes the second order brushed DC motor model in all joints. Such a model is used in order to incorporate and take into account all the most significant effects that can arise in highly coupled, underactuated and highly nonlinear system such a real biped humanoid robot is.

In Figs. 4 and 5, the stick diagram of the robot, footprints, position of CoP and the Projection of the Center of Mass (PCM) are shown during the walking and stair climbing. In Figs. 4a and 4b, the robot is placed 1.3m in front of the stairs. The height of the stairs is 17cm and the depth is 35cm. These values are considered as known and are used to calculate the step length for the walking in order to approach the stairs close enough to the stairs, and to determine the overall parameters for stair ascending[4]. Walking/climbing speed, the height of the foot for walking and walking/climbing direction are set manually to nominal values as for the basic walk. In Fig. 4a the robot makes two steps to approach the stairs. After the foot contact with the ground is established at the end of the second half-step, the distance from the stairs was 11.0cm. This information is used to switch from walking gait type to stair climbing. When the final stair is reached, the robot switches back to walking on a flat surface, with the overall parameters for the basic walk.

In Fig. 4b the robot changes its step length in order to make three shorter half-steps. That means that the distance from the stairs is such that to the robot can choose between shorter and longer steps. In the case of shorter steps, the distance of the foot to the stairs after the third half-step was 3.3cm (comparing with 11cm in the simulation result shown in Fig. 4a). This also illustrates the case when robot estimate distance to the stairs and position of the foot in front of it is not always the same as expected. The ability of a robot to make different step length when approaching the stairs is important in the case when approaching speed varies. In that case the robot can decide the number of approach steps by basic speed-step length relationship which is related to metabolically optimal walking patterns [21].

For the simulation experiments shown in Figs. 4a and 4b, the information about the geometry of the stairs was used precisely. However, the real robots, which are usually equipped with a vision system, need to estimate the dimensions of the stairs. This estimation is always prone to error, and thus the control system needs to be robust to those uncertainties. Fig. 4c shows the simulation experiment when the robot is climbing the stairs with each stair having a different height from the ones known to the controller. The first stair is 17cm high, second is 15cm, third is 16cm while the fourth is 18cm high. For determining the parameters of gait, the control system used the values of 16cm for height and a 35cm for depth of each stair. The robot successfully can climb the stairs even if the height and depth of the stairs are different from those known to the controller. This is an important property of proposed motor control system, i.e. the dynamic balance controller that can compensate (to a certain extent) the disturbances from unexpected feel strike that appear as a result of an error from vision or some other sensory system.

In simulation shown in Fig. 5, robot is modifying on-line the climbing direction. This illustrates the ability of motor control system to change the robots direction during stair ascending in order to avoid an obstacle or another biped or human that is also at the stairs. For the first two stairs, the robot is changing its climbing direction by 10^o to the right on each stair. From thirst third stair and onward, the robot is changing its direction to the left, again by 10^o.

[4]Based on the experience, humans can estimate the height and depth of the stair, as well as the distance to the stairs. That is why it is justified to consider these values as being approximately known to the robot.

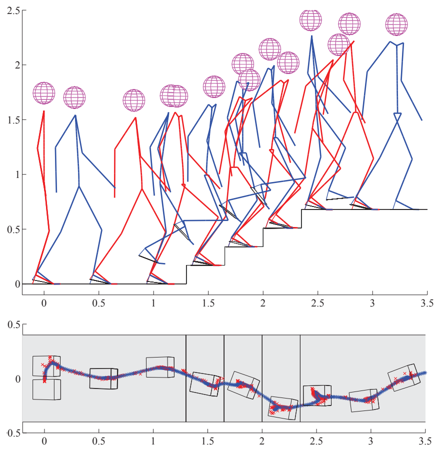

Fig. 5. Stick diagram of the robot, footprints, position of the CoP (red crosses) and PCM (blue stars) when the direction of motion when ascending stairs was changed on-line.

VI. CONCLUSION

In this paper is presented the motor control system based on RAMPs, with the realization of walking and stair ascending gaits. The controller is using RAMPs for synthesis and realization of the desired motion of the robot's joints. It is shown that the same set of RAMPs is used to realize different types of gaits: walking on a flat surface and stair climbing.

The presented simulation results showed that RAMP based method for the synthesis and realization of robot gaits can generate behaviors similar to those of humans. Inspired by the human's behavior, it is shown that the robot can approach the stairs with shorter or longer half-steps while preserving the ability to smoothly transfer to stair ascending, and back to walking on flat surface. Further, it is shown that the control system is robust to the uncertainties related to the geometry of the stairs and robot can successfully climb the stairs when the dimensions of each stair step are different from the values known to the controller. The last simulation showed that robot can modify the gait on-line and change its direction any time to avoid different types of obstacles even when climbing stairs.

The future work will be focused on the synthesis of the motion for descending the stairs. The goal will be to integrate the realization of stair descending into the same controller presented here and to show that the same universal motor control system can be used to realize this gait type as well.

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