# Locomotion Planning and implementation of Humanoid Robot Robo-Eectus Senior (RESr-1)

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***Abstract*— This paper presents design, control and implementation of the humanoid robot platform Robo-Erectus Senior (RESr-1). It is a full-size humanoid robot using self-contained modular component to perform cooperative works in general humanoid environment and robotic soccer (RoboCup) in particular. Mechatronic drives has cubic or double design with multiple connecting sockets in different orientations. Thereby, actuators, passive joints, rigid links can be rapidly assembled with various configurations having different kinematics and dynamic characteristics. In RESr-1, serial connected legs are parallel connected and controlled with individual controller. Based on the hierarchical control concept, low level trajectory are generated by decomposing locomotion into key poses as observed in humanoid locomotion. These poses are connected by sine, cosh and third-order interpolation functions. Thereby, walking pattern trajectories can satisfy continuity, smoothness with simple mathematical form. Simple locomotion planning methods for biped walking, turning and kicking are described. The proposed method provides a set of standard parameters for further optimization and learning with feedback information. It has been tested on RESr-1, which gave a outstanding exhibition in the Humanoid League of RoboCup2007. As shown in the experimental result, gaits are stable with various parameter value of stride length, pace time and double support phase ratio.**

***Index Terms*—*Biped robot, Walking pattern generation, Walking, Turning, Kicking***

## I. Introduction

Recently, significant progress has been made in the field of humanoid robotics, particularly with the initiative of RoboCup Humanoid league to promote robotics and Artificial Intelligence research, by offering publicly appealing, but formidable challenges. Overcoming these challenges requires careful investigation and fostering of various technology areas including electronics, signal processing, mechanics, control engineering and many other disciples.

RESr-1 is a full-size humanoid robot developed by the Advanced Robotics and Intelligent Control Centre (ARICC), Singapore Polytechnic. The objective of RESr project is to develop the humanoid with more human-like features and human-friendly character. It has 19 degree of freedom, 150cm height and 40kg weight. The design concepts of RESr-1 are modular, compact and able to perform cooperative works in general and robotic soccer (RoboCup) in particular.

Such a complex system is difficult to plan and control exactly to the required specifications. In the field of locomotion control, many related researches have studied offline and online biped gait generation methods. Mostly, the dynamic walking control strategy plan and modify biped walking with consideration of Zero Moment Point [1] trajectory or other balancing criterion [2] [3].

In this paper, basic gait pattern of walking, turning and kicking as required in soccer game is planned in a simple and an efficient way. It provides a easy way to operate the robot with simple mathematical form and smooth locomotion properties. Further optimization via Estimation of Distribution Algorithm and related experiment and analysis [4] [5].

For straight walking, similar to the method shown in [6] and [7], sine, cosine and 3rd order polynomial functions are used to generate basic joint angles during biped walking. Walking pattern can be easily changed in stride length, pace time and double support phase ratio continuously. With feedback joint angle, angular velocity, tilt information and moving direction, ZMP trajectory and vibration reduction function can work online. As tested by experiment, ZMP trajectories constrain in stable region with enough margin. It proves the dynamical stability of biped walking generated by the proposed method.

Turning is decomposed into two periods as turning and recovering. Robot makes turn during the first phase and comes back to stand phase during the second phase. Kinematic difficulty comes from the coupling of sagittal and frontal planes caused by turning motors in thighs. Joint angles are carefully calculated to avoid foot landing during turning. Only maximum of $20^\circ$ can be achieved at the original site because of foot length constraint. Same kind of calculation can be applied on turning in walking. It will be investigated in future research.

Different from the previous two movements, kicking requires more on velocity and acceleration to achieve energetically locomotion. Instead of joint position, kicking is generated from velocity and acceleration plan. So robot can touch the ball with maximum velocity and thereby kick it with maximum force. According to velocity variation, kicking leg speeds up from rear, reaches possible kicking range and speeds down after kicking. $x$ coordinate with maximum velocity is defined ”Most Efficient Kicking Range”. Kicking is preferred to happen during this period for large power. While $x$ coordinate with velocity larger than minimal one to move the ball is defined as ”Possible Kicking Range”. Ball can be moved during this area, but may not impactful. With the help of vision information, robot shall kick only when ball is in the Possible Kicking

Range and best kick when ball is in the Most Efficient Kicking Range.

All these locomotion are generated following strict formulations. It is the basis for next step optimization and learning. All three actions have been tested successfully on Robo-Erectus Senior , which was awarded the fourth place in penalty kick of TeenSize Humanoid League of RoboCup 2007 at Atlanta.

The structure of this paper is as follows. Section 2 introduces the hardware structure of Robo-Erectus Senior. Section 3 explains the basic locomotion generation method. Section 4 presents the findings from experiment. Conclusion and future work are exhibited in Section 5.

## II. Hardware Description

### A. Mechanical Structure

Modular design concept is employed in the development of RESr. A modular biped robot system consists of a set of independently designed modules, such as actuators, passive joints, rigid links (connectors) that can be rapidly assembled into a complete robot with various configurations having different kinematics and dynamic characteristics.

Off-the-shelf intelligent mechatronic drives, PowerCube, are selected as actuator modules for rapid deployment. Each of the actuator modules is a self-contained drive unit with a built-in motor, a controller, an amplifier, and the communication interface. It has a cubic or double-cube design with multiple connecting sockets so that two actuator modules can be connected in many different orientations. To facilitate the forward kinematics analysis, an angular displacement sensor is built into each of the passive rotary and pivot joint modules. A set of rigid links with various geometrical shapes and dimensions has been custom-designed to connect joint modules.

Final dimensional parameters of Robo-Erectus Senior after repeated experiments and optimization are shown in Table I.

TABLE I

Physical Specifications of Robo-Erectus Senior

| | | | | | |
|---|---|---|---|---|---|
| 1. Physical Specifications | | | | | |
| Weight | Dimensions | | | Speed | |
| | Height | Width | Depth | Walking | Running |
| 42kg | 150cm | 27cm | 20cm | 3.4mts/min | — |
| 2. Degrees of Freedom | | | |  | |
| Joint | Roll | Pitch | Yaw | | |
| Head | | | ✓ | | |
| Shoulder | ✓ | ✓ | | | |
| Elbow | | ✓ | | | |
| Hip | ✓ | ✓ | ✓ | | |
| Knee | | ✓ | | | |
| Ankle | ✓ | ✓ | | | |
| 3. Sensors | | | | | |
| Sensor | Details | | | | |
| Camera | 320x240 Resolution 30fps. | | | | |
| Compass | $1^\circ$ heading accuracy. | | | | |
| Tilt | Two dimensions. | | | | |
| Sonar | Distance range 5cm–250cm. | | | | |
| 4. Specifications | | | | | |
| Features | Main Processor | | Vision | | Sensor/Actuator |
| Processor | Intel Celeron | | Intel Core Solo | | Dual PIC18F8720 |
| Speed | 800Mhz | | 1.33GHz | | 25Mhz |
| Memory | 1GB | | 1GB | | 8KB |
| Storage | 30GB | | 16GB | | 256KB |
| Interface | CAN BUS, USB, WIFI | | USB, WIFI | | RS232, RS485 |

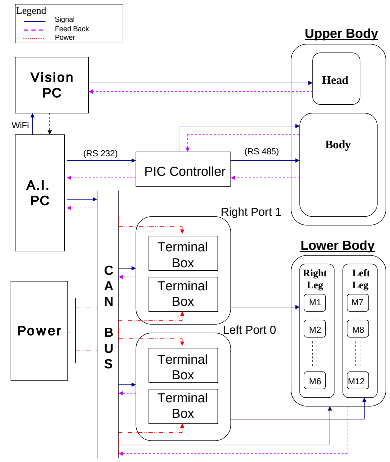


Fig. 1. Control structure of Robo-Erectus Senior.

### B. Electronic system

Because the active modules are self-contained mechatronic units, the control loop of the robot is closed at the joint level. Each actuator module has its own individual motion controller. The inter-module communication is through the CAN-bus protocol and the RS-485 serial interface. Based on hierarchical control concept, low-level trajectory generation and control are developed. Once the robot is fully constructed, configured and initialized, the AI PC is able to identify the configuration of the robot, generate the necessary models, and coordinate the motion control of the robot.

Torque and power requirements of the actuators (brushless servo motor) used in Robo-Erectus Senior were carefully chosen to enable walking, playing soccer and climbing stairs. Maximum output torque and angular velocity of the actuator are 45Nm and $238^\circ$/sec.

The onboard computer Sony VAIO ultra portable PC is equipped on Robo-Erectus Senior for vision processing, robot navigation and localization. Multiple color objects can be detected in one image. From the parameters of the objects in the image ($x$, $y$ coordinates and objective size) and the known orientation of the cameras, physical position of the objects relative to the robot can be calculated.

Tilt sensor and an electronic compass is set in upper body to get the tilt information and to measure the moving direction. Besides that, two monocular USB cameras with standard miniature lenses are used to give a large vertical coverage. The frame rate is 30Hz for $640\times480$ with automatic control of exposure, gain and black level. Robo-Erectus Senior can work continuously with equipped Lithium-polymer batteries for a period of 30 minutes. The block diagram for locomotion control and vision administration is shown in Fig.1.

## III. Locomotion planning

In this section, suitable walking patterns design for dynamic biped walking, turning and kicking are described.

### A. Walking

*1) sagittal view:* Since ankle position is the superposition of a linear curve and a sin curve which has zero velocity at the start and the end, maximum velocity in the swing phase, swing ankle $(x_\mathrm{a}, y_\mathrm{a}, z_\mathrm{a})$ and pelvis $(x_\mathrm{p}, y_\mathrm{p}, z_\mathrm{p})$ trajectories in the local coordinate frame can be set as

$$\begin{aligned} x_\mathrm{a}(t) &= (s_b + s_f)(\frac{t-(t_1+t_d/2)}{(t_2-t_1-t_d)} \\ &\quad -\frac{1}{2\pi}\sin(2\pi\frac{t-(t_1+t_d/2)}{t_2-t_1-t_d})) - s_b, \quad (1) \\ x_\mathrm{p}(t) &= \sum_{i=0}^{3} a_i(\frac{t-t_1}{t_2-t_1})^i. \quad (2) \end{aligned}$$

Moreover, shape factor $\alpha$ is used to find the proper shape for various walking conditions and to change the dynamic property of forward walking. Since the average velocity during one gait cycle is $(s_b+s_f)/(t_2-t_1)$, the recommended range of $\alpha$ is $[0.5\times((s_b+s_f)), 4\times(s_b+s_f)]$ for normalized time period (see Fig. 2).

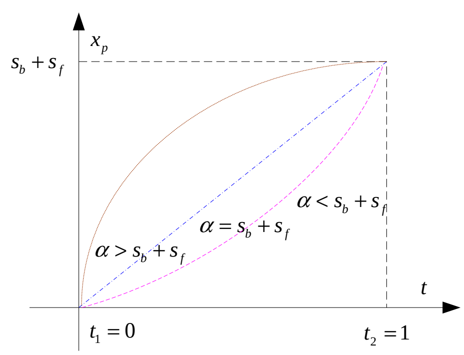


Fig. 2. range of the parameter $\alpha$ and the corresponding $x_p$ trajectory.

$$\begin{pmatrix} x_\mathrm{p}(0) \\ \dot{x}_\mathrm{p}(0) \\ x_\mathrm{p}(1) \\ \dot{x}_\mathrm{p}(1) \end{pmatrix} = \begin{pmatrix} -s_b/2 \\ \alpha s_b \\ s_f/2 \\ \alpha f \end{pmatrix}$$

*2) frontal view:* Let $\alpha_1$ be the velocity multiplier for the start and the end of each step; $\beta_1$ be an amplitude multiplier at middle point $t_j = 0.5$; $v_y$ and $s_y$ be scale factors for $\alpha_1$ and $\beta_1$ (default value is 1 for forward walking). Then it leads

$$\tilde{y}_\mathrm{p}(t) = \sum_{i=0}^{3} \tilde{c}_i(2t)^i,$$

where $\tilde{y}_\mathrm{p}(0) = 0$, $\dot{\tilde{y}}_\mathrm{p}(0) = -\alpha_1 v_y$, $\tilde{y}_\mathrm{p}(1/2) = -\beta_1 s_y$, $\dot{\tilde{y}}_\mathrm{p}(1/2) = 0$.

$$\tilde{y}_\mathrm{p}(t) = \sum_{i=0}^{3} \tilde{c}_i(2t-1)^i$$

where $\tilde{y}_\mathrm{p}(1/2) = -\beta_1 s_y$, $\dot{\tilde{y}}_\mathrm{p}(1/2) = 0$, $\tilde{y}_\mathrm{p}(1) = 0$, $\dot{\tilde{y}}_\mathrm{p}(1) = \alpha_1 v_y$.

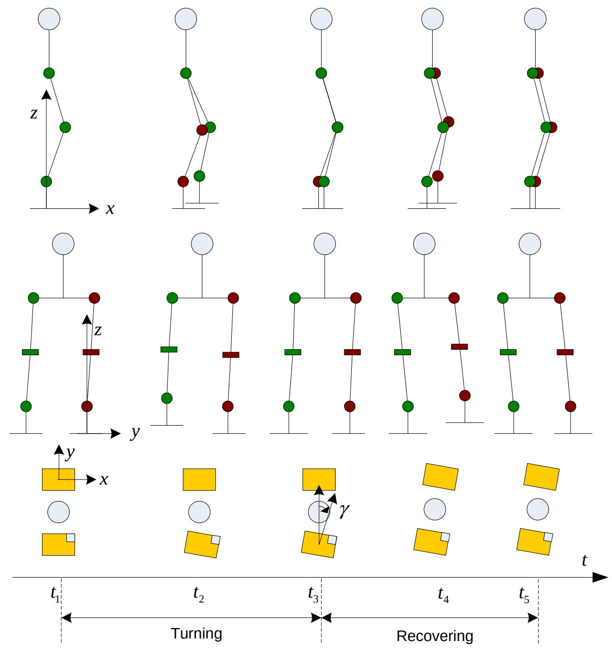


Fig. 3. Plan turn walking in angle space.

*3) Constraints in joint space:* Let single support time $T_s = \alpha_s \times T$ $(0 < \alpha_s < 1$, $T$ is step time). Since motor acceleration $|\ddot{\theta}| < 8.73/s^2$, variation region of joint angles during single support phase limits in $2.18\alpha^2 T^2$. It is used in time scale design, for example, if $T = 1$, minimal joint variation is $0.52$, then $\alpha > 0.49$.

### B. Turning

Similar to the principle observed in human movement, turning locomotion is decomposed into turning and recovering periods as shown in Fig. 3. Turning leg swings up, turns specified angles at $t_2$ and touches the ground during the turning phase $[t_1, t_3]$. Followed with it, the supporting leg swings up as well to let the turning leg recovers back at $t_5$ and then touches down during the recovering phase $[t_4, t_6]$.

Let $R_x(\alpha)$, $R_y(\theta)$ and $R_z(\phi)$ be basic rotation matrices for rotation about $OX$, $OY$ and $OZ$ with $\alpha$, $\theta$ and $\phi$ angle respectively. Position of left ankle $P_{la}$, left knee $P_{lk}$, left hip $P_{lh}$, right hip$P_{rh}$, right knee $P_{rk}$, right ankle $P_{ra}$ and right foot $P_{rf}$ can be achieved with the rotation matrices as

$$\begin{aligned} P_{la} &= [0,0,l_1]R_x(q_1)R_y(q_2) \\ P_{lk} &= P_{la} + [0,0,l_2]R_x(q_1)R_y(q_2)R_y(q_3) \\ P_{lh} &= P_{lk} + [0,0,l_3]R_x(q_1)R_y(q_2)R_y(q_3)R_z(q_4)R_x(q_5) \\ P_{rh} &= P_{lh} + [0,D_h,0]R_x(q_1)R_y(q_2)R_y(q_3)R_z(q_4) \\ &\quad R_x(q_5)R_y(q_7) \\ P_{rk} &= P_{rh} + [0,0,l_3]R_x(q_1)R_y(q_2)R_y(q_3)R_z(q_4)R_x(q_5) \\ &\quad R_y(q_7)R_x(q_8)R_z(q_9) \\ P_{ra} &= P_{rk} + [0,0,l_2]R_x(q_1)R_y(q_2)R_y(q_3)R_z(q_4)R_x(q_5) \end{aligned}$$

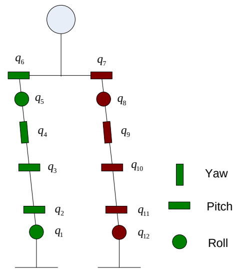


Fig. 4. Motor structure of biped robot.

$$
\begin{aligned}
& R_y(q_7)R_x(q_8)R_z(q_9)R_y(q_{10}) \\
P_{rf} \;=\; & P_{rk} + [0,0,l_1]R_x(q_1)R_y(q_2)R_y(q_3)R_z(q_4)R_x(q_5) \\
& R_y(q_7)R_x(q_8)R_z(q_9)R_y(q_{10}) \\
& R_y(q_{11})R_x(q_{12})
\end{aligned}
$$

Similarly, the rotation matrix from right support foot to left swing foot is with the sequence of $R_x(q_{12})$-$R_y(q_{11})$-$R_y(q_{10})$-$R_z(q_9)$-$R_x(q_8)$-$R_y(q_7)$-$R_x(q_5)$-$R_z(q_4)$-$R_y(q_3)$-$R_y(q_2)$-$R_x(q_1)$. The order of performing rotations is determined by the biped structure as shown in Fig. 4.

To turn robot $\gamma$ angle (left is positive and right is negative) with right leg, $q_9$ should be $\gamma$. Problem exists in keeping the swing foot horizontal contemporarily. Sagittal plane and frontal plane is connected by the turning motor at thighs. It is hard to decompose the coupling brought by $q_9$ during the swing phase and the recovering phase.

For swing phase, swing ankle joint angle $q_{11}$ and swing foot joint angle $q_{12}$ are set as

$$
\begin{aligned}
q_{12} &= -asin(\frac{\sqrt{(p_{rk,y}-p_{ra,y})^2+(p_{rk,z}-p_{ra,z})^2}}{l_2}), \\
q_{11} &= -asin(\frac{\sqrt{(p_{rk,x}-p_{ra,x})^2+(p_{rk,z}-p_{ra,z})^2}}{l_2}).
\end{aligned}
$$

While for recovering phase, left ankle joint angle and left foot joint angle are

$$
\begin{aligned}
q_1 &= -asin(\frac{\sqrt{(p_{lk,y}-p_{la,y})^2+(p_{lk,z}-p_{la,z})^2}}{l_2}), \\
q_2 &= -asin(\frac{\sqrt{(p_{lk,x}-p_{la,x})^2+(p_{lk,z}-p_{la,z})^2}}{l_2}).
\end{aligned}
$$

It will keep the swing foot parallel to the ground and avoid landing impact during turning.

### C. Kicking

Quality of kicking is mostly determined by the velocity at the kicking moment. Since momentum $I$ is the product of mass $m$ and velocity $v$, the larger the velocity is, the bigger the momentum is. Based on conservation of momentum and collisions, bigger momentum leads further rolling of ball for $t = I/f$, and sequentially better kicking, where $f$ is the friction.

By observing instep driving of human kicking, steps to following includes:

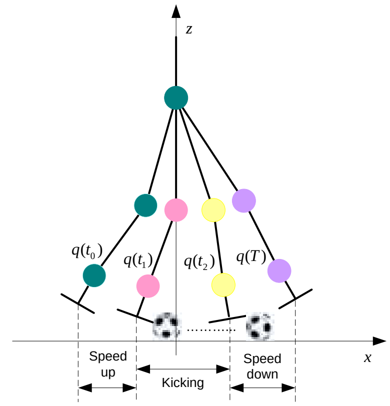


Fig. 5. Plan kicking in angle space.

1) Approach the ball from directly behind or from a slight angle; square hips and shoulders to the line of the kick;
2) With the balance foot behind the ball and the balance knee slightly flexed, kick hard into the center of the ball with instep;
3) Follow through in the direction of target.

Accordingly, kicking is divided into speed up, kicking and speed down three phases (see Fig. 5). Kicking leg accelerates to maximum velocity $q_{max}$ in the first phase, dribbles up the ball and kicks it away during kicking phase, finally it decelerates to zero velocity at the end of speed down phase.

As show in Fig. 6, let joint velocity go as

$$
\dot{q} = \begin{cases} q_{max}\sin(\frac{t\pi}{2t_1}), & 0 < t \le t_1; \\ q_{max}, & t_1 < t < t_2; \\ q_{max}\sin(\frac{\pi}{2} + \frac{\pi(t-t_2)}{2(T-t_2)}), & t_2 \le t < T. \end{cases} \tag{3}
$$

Then it gets

$$
q = \begin{cases} -q_{max}\frac{2t_1}{\pi}\cos(\frac{t\pi}{2t_1}) & 0 < t \le t_1; \\ +q_{max}t_1 + c, & \\ q_{max}t + c, & t_1 < t < t_2; \\ -q_{max}\frac{2(t-t_2)}{\pi}\cos(\frac{\pi}{2} + \frac{\pi(t-t_2)}{2(T-t_2)}) & t_2 \le t < T. \\ +q_{max}t_2 + c, & \end{cases} \tag{4}
$$

With given $q(0)$ and $q(t_1)$, we have $c = q(t_1) - \frac{\pi}{2}(q(t_1) - q(0))$, $q_{max} = \frac{\pi}{2t_1}(q(t_1) - q(0))$. Thereby, $\dot{q}$ and $q$ are achievable.

According to $x$ coordinate of the swing foot $x_f$=$l_t \times \sin(q_h) + l_c \times \sin(q_k)$ (where $l_t$ and $l_c$ are length of thigh and crus, $q_h$ and $q_k$ are hip and knee joint angles), we define the range of $[x(t_1), x(t_2)]$ as the "Most Efficient Kicking Range" because of the large velocity during this period and define $[x(0), x(T)]$ as the "Possible Kicking Range".

## IV. Experimental Result

The proposed method is applied on Robo-Erectus Senior platform. Fig.7 shows the ZMP trajectory of forward walking with feedback parameters. It goes continuously from left foot to right foot iteratively as stable region changes from left supporting area to right supporting area.

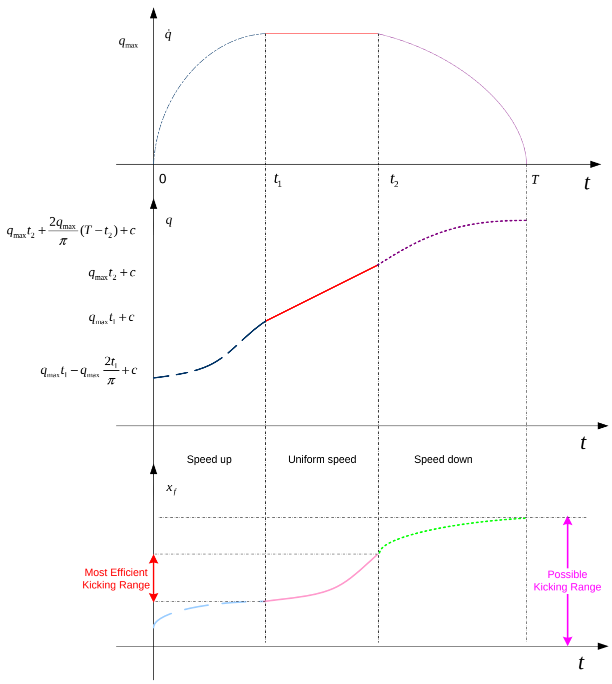


Fig. 6. Trajectory and velocity of joint angle during kicking.

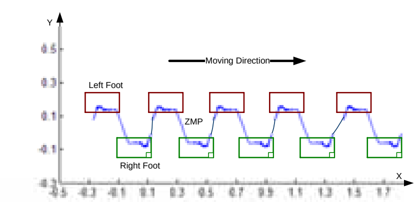


Fig. 7. ZMP trajectory during walking.

The feedback joint angles in forward walking is shown in Fig.8. It is smooth and continuous as designed by the proposed method. Since gait cycle costs 2 second per half step, joint angels repeat every 4 second.

Walking frames are collated below in Fig.9. Walking begins from standing pose, takes the first half step for initial walking pose and circulates biped walking. It stops with last half step and returns back to standing pose. Stride length can change from 0 to 40cm. Range of pace time is [5.5sec, 7sec].

Similarly, frames for kicking is exhibited in Fig.10. The corresponding ZMP trajectory is shown in Fig.11. ZMP moves forward as the kicking leg swings forward to finish kick. But it stays in supporting foot (left foot) during kicking. That is, robot keeps balance as kicking leg switches out to finish kick even with as large angular velocity as 400°/sec.

Joint angles for kicking is presented in Fig.12. It can be found that, supporting leg (left leg) keeps steady during kicking, while the kicking leg (right leg) moves continuously. Kicking ankle and knee are the most intensively used two joints. They changes from 39.9° to 20.4° and from 30.0° to -4.7° respectively. They are the main factors to provide power for kicking. Compared with that, variation of kicking hip (from

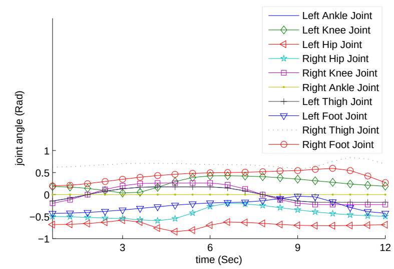


Fig. 8. Joint angles for forward walking.

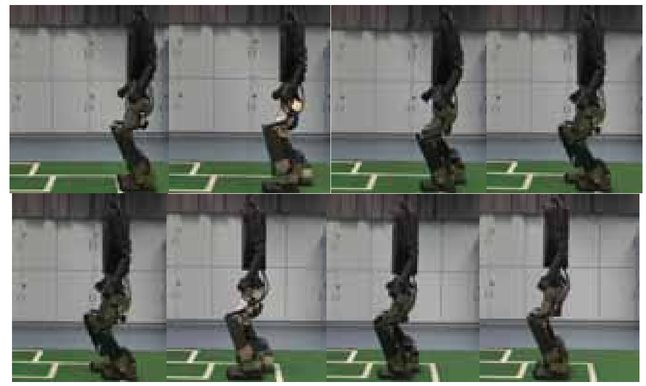

Fig. 9. Forward walking frames.

-1.3° to -12.3°) is small because large variation of hip may cause vibration and instability.

Fig.13 is the sequence of frame for turning left. ZMP trajectory goes like a circle from left support foot to right support foot, returns back to the original point (middle point between two feet) after turning. Because of foot length limitation, maximum turning angle without moving forward is 20°/sec for Robo-Erectus Senior. Each turning takes about 6 seconds. The joint angles for turning in 6.7 seconds is given in Fig.15.

## V. Conclusion

Simple walking pattern generation method is proposed in this paper for biped walking, turning and kicking, which is continual in stride length and pace time.

Straight walking trajectory is planned in Cartesian coordinate space using sine function, which has slow ending and

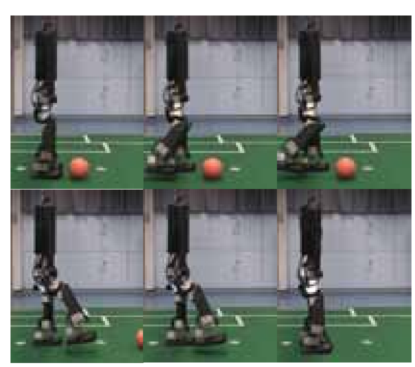

Fig. 10. Kicking frames.


Fig. 11. ZMP trajectory during kicking.

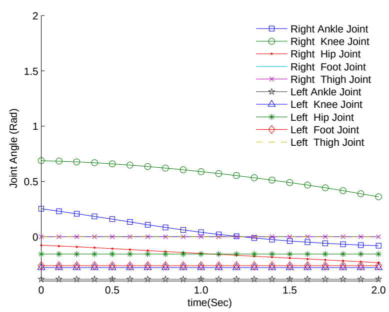


Fig. 12. Joint Angles for kicking.

Fig. 13. Turning frames.

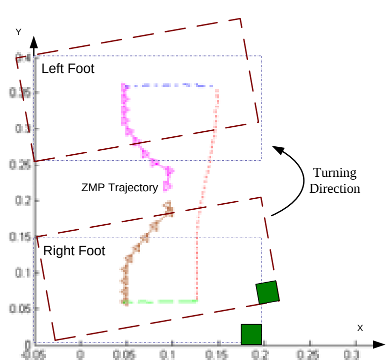


Fig. 14. ZMP trajectory during turning.

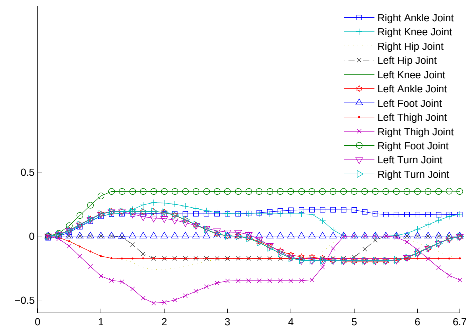


Fig. 15. Joint angles for turning.

fast central section. It makes the robot easy to reduce landing impact and damp body vibration. All key poses in locomotion selected according to human movement, is connected by third order polynomial function. Besides of the advantage of continuity in the defined time interval, the connection function has standard coefficient with normalized time scale. By using this kind of function, robot can change its joint angular position and velocity continuously during its boundary condition.

The proposed method has basically proved by locomotion experiment. Stable walking pattern can be achieved simply by tuning gait length, time, double ration and so on few factors.

It provides the standard parameters for next step optimization and learning. By setting force sensor on the sole, future work will be taken more on landing impact reduction. It helps to accelerate walking.

## VI. Acknowledgements

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## References

[1] M. Vukobratovic and B. Borovac, "Zero moment point-thirty five years of its life," *Int. Journal of Humanoid Robotics*, vol. 1, no. 1, pp. 157–173, 2004.

[2] J. Kim, I. Park, and J. Oh, "Experimental realization of dynamic walking of biped humanoid robot khr-2 using zmp feedback and inertial measurement," *Advanced Robotics*, vol. 20, no. 6, pp. 707 – 736, June 2006.

[3] S. Kagami, T. Kitagawa, K. Nishiwaki, T. Sugihara, M. Inaba, and H. Inoue, "A fast dynamically equilibrated walking trajectory generation method of humanoid robot," *Autonomous Robots*, vol. 12, no. 1, pp. 71–82, 2002.

[4] L. Hu, C. Zhou, and Z. Sun, "Hybrid estimation of distribution algorithm with application to biped gait generation," *Information Sciences*, 2006 (accepted).

[5] ——, "Estimating biped gait using spline-based probability distribution function with Q-learning," *IEEE Trans. on Ind. Elec.*, 2006 (accepted).

[6] I.-W. Park, J.-Y. Kim, J. Lee, and J.-H. Oh, "Online free walking trajectory generation for biped humanoid robot khr-3(hubo)," in *Proc. IEEE Int. Conf. on Robotics and Automation*, Orlando, Florida, US, May 2006, pp. 1231–1236.

[7] Q. Huang, K. Yokoi, S. Kajita, K. Kaneko, H. Arai, N. Koyachi, and K. Tanie, "Planning walking patterns for a biped robot," *IEEE Trans. on Rob. and Aut.*, vol. 17, no. 3, pp. 280–290, 2001.