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Walking Pattern Generation of Dual-Arm Mobile Robot Using Preview Controller

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Abstract: Based on the stability request of robot's moving on the ground, the motion planning of dual-arm mobile robot when moving on the ground is studied and the preview control system is applied in the robot walking pattern generation. Direct question of robot kinematics in the extended task space is analyzed according to Degrees of Freedom configuration of the dual-arm mobile robot. It is proved that the preview control system could be used in the generation of robot Center of Mass forward trajectory through the building of double linear inverted pendulum model of dual-arm mobile robot. The sector gridding search algorithm is proposed and the reachable workspace which meets the Zero Moment Point stability principle when the robot moving on the ground is obtained. Tip Trajectory is generated through polynomial interpolation. Each joint curve is calculated using MATLAB which is imported to virtual physical model. The feasibility of gait generation is verified.

Keywords: Extended task space, piecewise polynomial interpolation, sector gridding search algorithm, ZMP stability criterion

INTRODUCTION

Mobile robotics is a hot topic of research in the field of robotics. According to the different mobile mode, mobile robot can be classified as wheeled mobile robot and legged mobile robot. However, all of these developed mobile robots which move on the ground have disadvantages of single mobile ability and poor adaptability to environment. Most of them move on the continuum surface or in the pipeline which cannot move on discontinuous media. Biped robots keep moving in half-space below the waist and walking on the ground through foot, alternately serving as the support foot and swing foot. They do not have the ability to grab truss bar through foot making them not suitable for moving in the small space within space truss. A dual-arm mobile robot which is a novel redundant robot can walk on the ground with the hands touching and swinging alternately in the whole reachable workplace. It is different from a biped robot.

The main differences of motion planning methods are building environment models such as gridding (Takuya *et al*., 2008), probabilistic roadmap (Lydia *et al*., 1996), visibility graph (Kuwata and How, 2004) and Voronoi method (Hiroto *et al*., 2008). For the unilateral and under actuated characteristics of legged robot, the Zero Moment Point (ZMP) stability criterion (Vukobratovic and Borovac, 2004) must be satisfied when robot walks on the ground. Many well-known humanoid robots such as ASIMO (Chestnutt *et al*., 2005), HRP-3 (Akachi *et al*., 2005) and HUBO (Kim *et al*., 2006) have extraordinarily reliable biped walking ability.

Huang *et al*. (1999) planned the foot trajectory which satisfied ZMP stability criterion by third order spline interpolation. Kajita *et al*. (2003) designed preview control in which the ZMP and Center of Mass (COM) were obtained by forecasting the future walking information. They also obtained the gait patterns when robot walked on spiral stairs. Park and Youm (2007) controlled the biped robot on-line by improving preview controller. Dual-arm mobile robot which is a legged robot should satisfied ZMP stability criterion when it walks on the ground. Therefore, preview controller is applied in walking pattern generation of the dual-arm mobile robot. The closed-form solution of each joint is obtained by taking advantage of extended task space method. Finally, the feasibility of this scheme is verified in the virtual physical environment.

METHODOLOGY

Dual-arm mobile robot:

Walking cycle: The dual-arm mobile robot has eight Degrees of Freedom (DOF) as illustrated in Fig. 1. The robot whose two arms are symmetric includes left arm, middle platform, right arm and a power. Each arm that includes hand and forearm has a pitch and a roll DOF at wrist and elbow joint, respectively. The two arms are connected by the middle platform. The platform board and four connecting terminal pads compose the middle platform with each side having a connecting terminal pad.

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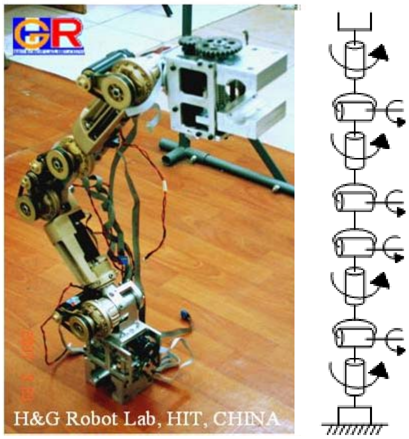

Fig. 1: DOF configuration of dual-arm mobile robot

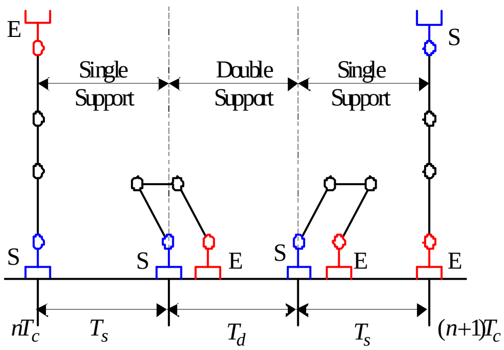

Fig. 2: Walking cycle of dual-arm mobile robot

As shown in Fig. 2, the original support hand is named as S-hand and the original swing hand is named as E-hand. At every initial and terminable moment of one step, the dual-arm mobile robot is always upright. The process by which the E-hand touches the ground and S-hand swings to upright is called one step of dual-arm mobile robot. One step could be divided into single support phase, double support phase and single support phase. The time spent on the single support phase is T_s while that spent on the double support phase is T_d. Therefore, one step period T_c is given by $2T_s+T_d$.

Kinematics based on extended task space method: The dual-arm mobile robot is limited to moving in a forward plane and the four roll DOF are locked. For the dual-arm mobile robot whose swing hand moves in a plane, the swing hand pose can be defined by two position components and one orientation angle. The kinematics equation for the dual-arm mobile robot is given as:

$$X = F(q) \tag{1}$$

where, X is a 3×1 dimensional vector in task space, q is a 4×1 dimensional vector in joint space and F is a 3×1:

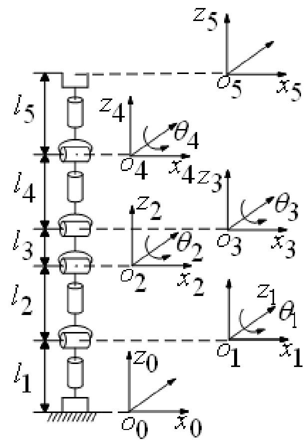

Fig. 3: Coordinates of dual-arm mobile robot

vector function. For the dual-arm mobile robot, the joint space dimension is four and the task space dimension is three. The difference of the joint space dimension and the task space dimension is called the degree of redundancy. To make use of the degree of redundancy, useful additional constraints have to be defined. This function should be expressed in terms of joint variables. Let the function be defined as:

$$X_e = F_e(q) \tag{2}$$

where, X_e is an r×1 dimensional vector in the extended task space, F_e is an r×1 dimensional vector function which is continuously differentiable for q and r is the degree of redundancy. The forward component of the position of COM is defined as X_e. Combining Eq. (1) and (2), the kinematics of the dual-arm mobile robot based on extended task space is:

$$X' = \begin{bmatrix} X \\ X_e \end{bmatrix} = \begin{bmatrix} F(q) \\ F_e(q) \end{bmatrix} \tag{3}$$

The coordinates system of dual-arm mobile robot is shown in Fig. 3. When the robot moves in x or z directions and rotates in y direction in the plane, the pose of the origin of dynamic coordinate $\{O_5\}$ is thick-and-thin relating to dynamic coordinate $\{O_4\}$. The position of the origin O_4 in base coordinate is defined as $(x_4, 0, z_4)$ and the orientation angle that rotates in y direction as β. The constraints relating to position and orientation of end-effectors are:

$$x_4 = l_2 S_1 + l_3 S_{12} + l_4 S_{123} \tag{4}$$

$$z_4 = l_1 + l_2 C_1 + l_3 C_{12} + l_4 C_{123} \tag{5}$$

$$\beta = \theta_1 + \theta_2 + \theta_3 + \theta_4 + i\,.2\pi\,,\ \beta \in (0, \pi) \tag{6}$$

The forward component of the position of COM is defined as X_e. If it is assumed that each COM lies on the geometric center of every link, the position of the total COM in base coordinate is found through homogeneous transformation. The forward component is expressed as:

$$x_{com} = \sum_{i=1}^{4} \frac{a_i}{a_0} l_{i+1} S_{1234} \tag{7}$$

where,

$$a_0 = m_1 + m_2 + m_3 + m_4 + m_5$$

and

$$a_i = \frac{m_{i+1}}{2} + \sum_{j=i+2}^{5} m_j \, (i = 1,\ldots,4)$$

The constraints of direct kinematics are found by combine Eq. (4)-(7). Given the end-hands task and additional task, the joint angles are acquired by solving the nonlinear equations.

Trajectory generation based on preview control system:

Desired ZMP: ZMP stability criterion should be satisfied when the dual-arm mobile robot walks on the ground, which is a condition to prevent robot falling down. According to the criterion, ZMP should be strictly within the support convex formed by the support hand if robot walking on the ground stably. In single support phase, the desired ZMP is set at the center point where the support hand contact with the ground is named as foothold. The n^{th} foothold point can be formulated as:

$$p^{(n)} = p^{(n-1)} + step \tag{8}$$

where, *step* is the forward step length, *n* is the number of steps. The position of first support hand is $p^{(0)}$ and the walking step begins with the S-hand touching the ground.

Inverted pendulum model of dual-arm mobile robot: If it is assumed that the mass of dual-arm mobile robot focuses on the COM of robot, the robot can be represented by a 2D linear inverted pendulum, as illustrated in Fig. 4. In the figure, $p^{(n)}$ denotes the n^{th} foothold point. If COM of robot moves in line *z* direction and the height of COM is z_c when robot moves to $p^{(n)}$ vertically, the line z equation can be expressed as:

$$Z = k\,(x - p) + z_c \tag{9}$$

where, k is a constant. Contractility f can be decomposed as:

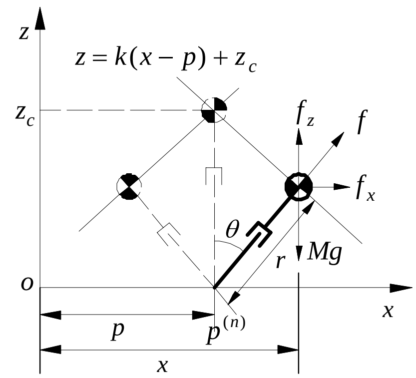

Fig. 4: Linear inverted pendulum model

$$f_x = f \sin\theta = \frac{x - p}{r} f \tag{10}$$

$$f_z = f \cos\theta = \frac{z}{r} f \tag{11}$$

In order to move COM in line *z* direction, the resultant force of contractility and gravity must be directed in line *z*. Therefore:

$$f_x : (f_z - Mg) = 1 : k \tag{12}$$

Combining Eq. (10)-(12) and simplifying using Eq. (9):

$$f = \frac{Mgr}{z_c} \tag{13}$$

Combining Eq. (13) and (10) and applying the under expression:

$$f_x = M\ddot{x} \tag{14}$$

The horizontal motion can be expressed as:

$$\ddot{x} = \frac{g}{z_c}(x - p) \tag{15}$$

Preview controller: Translating Eq. (15), robot dynamic model is expressed as:

$$p = x - \frac{z_c}{g}\ddot{x} \tag{16}$$

This is identical to car-table model (Kajita *et al.*, 2003; Kim *et al.*, 2006). where, *p* is the position of ZMP, *x* is the horizontal position of the cart (equal to the COM of the whole robot), z_c is the height of mass assumed as constant or changes along a slash and g is gravity acceleration. Defining a new variable u, the system state equation can be formulated as:

$$\frac{d}{dt}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u \tag{17a}$$

$$p = \begin{bmatrix} 1 & 0 & -\frac{z_c}{g} \end{bmatrix}\begin{bmatrix} x \\ \dot{x} \\ \ddot{x} \end{bmatrix} \tag{17b}$$

When the reference ZMP $p_d(i)$ is given from the desire ZMP, the performance index is defined by:

$$J = \sum_{i=k}^{\infty} \left\{ Q_e (p_d(i) - p(i))^2 + \Delta X^T Q_x \Delta X + R\Delta u(i)^2 \right\} \tag{18}$$

By solving discrete Riccati equation to minimize J:

$$u(k) = -k_e \sum_{i=0}^{k} (p(i) - pd((i) - K_x X(k) - \sum_{i=1}^{N_L} G(i) p_d(k+i) \tag{19}$$

where, N_L is the number of future steps to preview, K_s, K_x and $G(i)$ can be calculated by solving discrete optimal control problem.

The reachable workspace of single support phase: At single support phase, the dual-mobile robot is like a robotic arm whose foundation support is not fixed. Therefore, its reachable workplace should be determined and then the end-hand trajectory planned. The commonly used numerical approach for the determination of the workplace of robotic arm is Monte Carlo method. However, the foundation support of robotic arm is fixed on the ground and the palm of the support hand of dual-arm mobile robot touches the ground while is not fixed. Basing on this point, the industrial robot could do any motions within its joint range of activity. The support hand should always be hand touching and the determination of workplace should in be line with ZMP stability criterion. If the ZMP lies within the support polygon formed by the support hand and the sole keeps its position of ground touching, the robot cannot fall.

In order to enhance stability margin which ensures that the ZMP of the single support phase is always at foothold point, the gridding method is adopted to calculate the strong reachable workplace of the dual-arm mobile robot. This process is accomplished as follows:

- Circling with a radius of the total length of the robot and taking the first quadrant as the research object, successive gridding with the fixed step from the radial and the circumference direction is done. The right above starting point is taken as the first point, the circumference direction as the row vector and the radial direction as the column vector which stores the nodes into a matrix.
- Examine the points of the matrix successively from the first point. If the present point is reachable, move to the next point along the circumference direction. If the present point is unreachable, move to the next point along the radial direction.
- Store the examined reachable point into the new matrix, the strong reachable workspace boundary function could be achieved by the interpolation of these points.

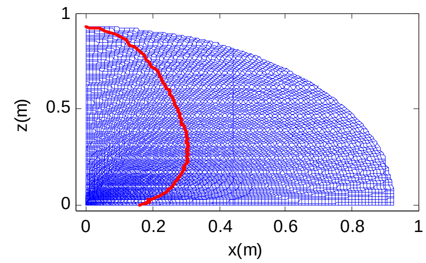

Fig. 5: Boundary of reachable workplace

Since only partial examination is conducted, the accuracy level of the boundary trajectory is related to the gridding. The denser the gridding, the more accurate the boundary trajectory achieved. Also, the amount of calculation is accordingly increased. The strong reachable workplace of the dual-arm mobile robot is shown in Fig. 5 with the longest ground walking step length as 0.16 m. It is only when the truss bar is within the strong reachable workplace that the dual-arm mobile robot's movement conversion from the ground to the truss bar is achieved.

End-hands trajectory generation: In the reachable workspace, the forward component of end-hand position and orientation angle can be found directly by adopting the cubic or quintic polynomial interpolation. The vertical component of end-hand position found by cubic or quintic polynomial interpolation cannot meet the ZMP stability criterion because of the restraint of reachable work space. Therefore, 2-3-2 piecewise polynomial interpolation passed through waypoint is adopted; selecting three curves, where the first and third curves select the quadratic curve and the second curve selects the cubic curve. The given initial and terminal points are $p_0(x_0, z_0)$ and $p_t(x_t, z_t)$. Selecting the middle points $p_m(x_m, z_m)$ and $p_d(x_d, z_d)$ as the successive waypoints, the three curves are:

$${}^1C : z = a_1(x + b_1)^2 + c_1 \tag{20a}$$

$${}^2C : z = a_2x^3 + b_2x^2 + c_2x + d_2 \tag{20b}$$

$${}^3C : z = a_3(x + b_3)^2 + c_3 \tag{20c}$$

The initial and terminal speeds of the robot are assumed to be zero so as to ensure that the dual-arm mobile robot walks steadily on the ground. From the nature of the second curve:

$$b_1 = -x_0,\ c_1 = z_0,\ b_3 = -x_t,\ c_3 = z_t$$

$$a_1 = \frac{z_m - z_0}{(x_m - x_0)^2}, a_3 = \frac{z_d - z_t}{(x_d - x_t)^2}, a_2 = \frac{2(v_1 - v_2 + v_3)}{(x_m - x_d)}$$

$$b_2 = \frac{v_1 - v_3}{x_m - x_d} - \frac{3(x_m + x_d)(v_1 - v_2 + v_3)}{(x_m - x_d)^2}$$

$$c_2 = 2v_1 - 3x^2_m a_2 - 2x_m b_2$$

$$d_2 = z_m - x^3_m a_2 - x^2_m b_2 \ x_m c_2$$

where,

$$v_1 = \frac{z_m - z_0}{x_m - x_0}, v_2 = \frac{z_m - z_d}{x_m - x_d} \text{ and } = v_3 = \frac{z_d - z_t}{x_d - x_t}$$

SIMULATION RESULTS

Simulation of walking one step on the ground: It is known from the strong reachable workspace that the longest ground walking step length of dual-arm mobile robot is 0.16 m. In this scope, the step length is chosen as 0.15 m. One step period $T_c = 7$ sec and consists of single support phase $T_s = 3$ sec and double support phase $T_d = 1$ sec. The curves at joint angles that change with time are shown in Fig. 6. The speed is shown in Fig. 7. From these curves it is that the changes of joint angles are continuous and smooth. It is only the angular accelerations which jump in some moments. This does not affect the continuity of joint angle curves; the curves of angular velocities are continuous and the curves of angular

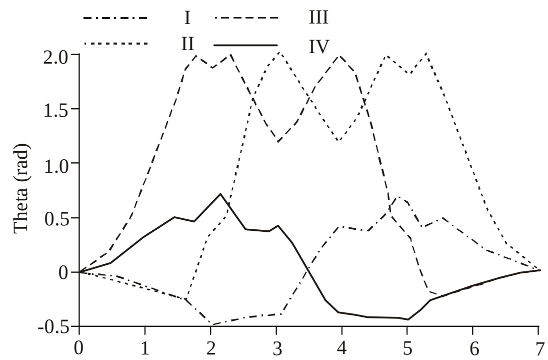

Fig. 6: Joints angle curves of dual-arm mobile robot

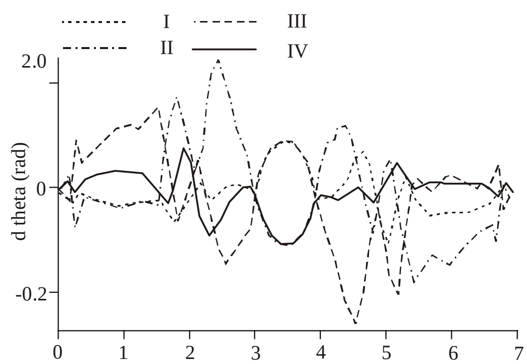

Fig. 7: Joints angle speed of dual-arm mobile robot

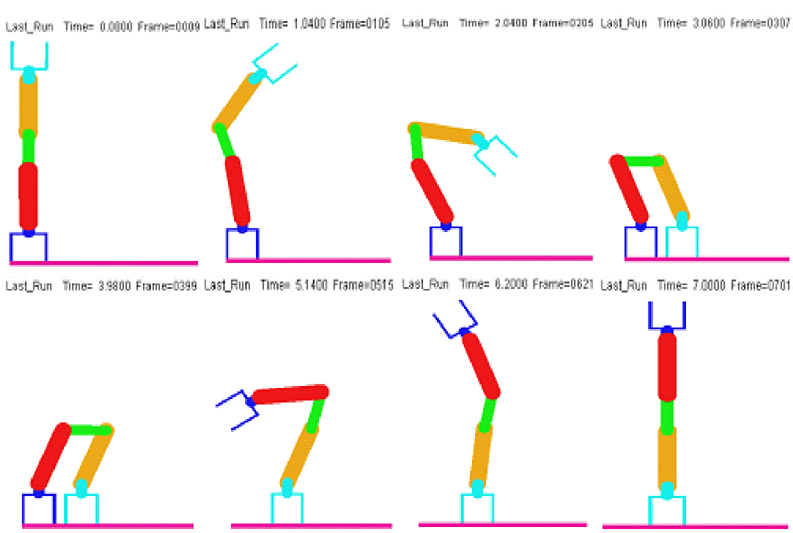

Fig. 8: Motion of dual-arm mobile robot in Adams

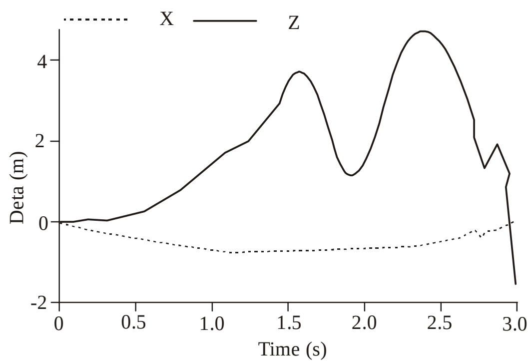

Fig. 9: Position errors of end-hand

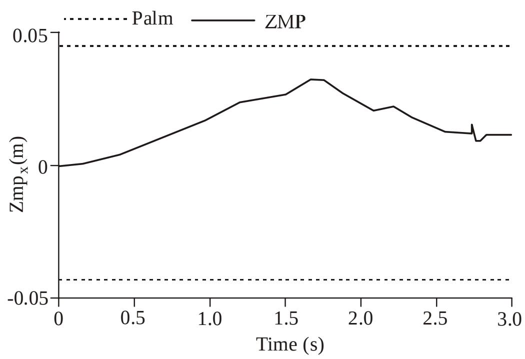

Fig. 10: Curves of ZMP changed with time

accelerations are discontinuous but it only affects the curvature of the joint angle curves.

The simple model of dual arm mobile robot was built according to the actual size and quality. At a set sample of 0.01 sec, the first step of walking on the ground is shown in Fig. 8. The movement of dual arm mobile robot is stable and there is no jumping and falling down. The end-hand position error in the first single support phase is given in Fig. 9. The horizontal end-hand position error is less than 0.001 m and the vertical end-hand position error is less than 0.005 m. The ZMP trajectory that changes with time in the first support phase is showed in Fig. 10. The ZMP point always remains at the range of 0.035 m, which restrains the dual-arm mobile robot from falling down when it is walking on the ground.

CONCLUSION

The motion planning of dual-arm mobile robot when moving on the ground is presented in this paper. The preview control system is applied in the robot motion planning and the COM forward trajectory is obtained through planning of desired ZMP. The sector gridding search algorithm is proposed and the reachable workspace which meets the ZMP stability principle when the robot moves on the ground is obtained. Tip Trajectory is generated through polynomial interpolation. The solution of each joint of redundant dual-arm mobile robot in the closed form is obtained basing on the extended task space method. The data curve is generated using MATLAB and the ADAMS virtual simulation used to verify the feasibility of the method proposed.

REFERENCES

Akachi, K., K. Kaneko and N. Kanehira, 2005. Development of humanoid robot HRP-3P. Proceedings of 5th IEEE-RAS International Conference on Humanoid Robots. Piscataway, NJ, USA, Dec. 5-5, pp: 50-55.

Chestnutt, J., M. Lau and G. Cheung, 2005. Footstep planning for the Honda ASIMO humanoid. Proceedings of the 2005 IEEE International Conference on Robotics and Automation (ICRA), Barcelona, Spain, April 18-22, pp: 629-634.

Hiroto, S., M. Yasuhiro and M. Fumio, 2008. Real-time motion planning in unknown environment: A Voronoi-based stRRT (spatiotemporal RRT). SICE Annual Conference, The university Electro-Communications, Japan, Aug. 20-22, pp: 2326 - 2331.

Huang, Q., S. Kajita and N. Koyachi, 1999. A high stability, smooth walking pattern for a biped robot. Proceedings of the 1999 IEEE International Conference on Robotics and Automation (ICRA), Detroit, Michigan, May 10-15, pp: 65-71.

Kajita, S., F. Kanehiro and K. Kaneko, 2003. Biped walking pattern generation by using preview control of zero-moment point. Proceedings of the 2003 IEEE International Conference on Robotics and Automation (ICRA), Taipei, Taiwan, Sep. 14-19, pp: 1620-1626.

Kim, J.Y., I.W. Park and J.H. Oh, 2006. Experimental realization of dynamic walking of the biped humanoid robot KHR-2 using zero moment point feedback and inertial measurement. Adv. Robot, 20(6): 707-736.

Kuwata, Y. and J. How, 2004. Three dimensional receding horizon control for UAVs. AIAA Guidance, Navigation and Control Conference, Providence, Rhode Island, USA, Aug. 16-19, pp: 2100-2113.

Lydia, E.K., S. Petr and C.L. Jean, 1996. Probabilistic roadmaps for path planning in high-dimensional configuration spaces. IEEE T. Robotic. Autom., 12(4): 566-580.

Park, J. and Y. Youm, 2007. General ZMP preview control for bipedal walking. Proceedings of the 2007 IEEE International Conference on Robotics and Automation (ICRA), Roma, Italy, April 10-14, pp: 2682-2687.

Takuya, K., T. Tomohito and M. Yasushi, 2008. The generation of environmental map based on a NDT grid mapping-proposal of convergence calculation corresponding to high resolution grid. Proceedings of the 2008 IEEE International Conference on Robotics and Automation (ICRA) Pasadena, CA, May 19-23, pp: 1874-1879.

Vukobratovic, M. and B. Borovac, 2004. Zero-moment point-thirty five years of its life. Int. J. Hum. Robot., 1(1): 157-173.