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Dynamic Reconfiguration Manipulability Analyses of Humanoid Bipedal Walking

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Abstract— **In this paper, we propose a new index of dynamic manipulability for humanoid robot to estimate dynamic ability to change configuration by using remaining redundancy, while prior task is being controlled, e.g., face and eyes being directed to some object. Several indexes have been proposed so far to measure statical and dynamical capability of robot manipulator. For example, Dynamic Manipulability Ellipsoid (DME) describes a distribution of hand acceleration produced by normalized joint torque. On the other hand, Reconfiguration Manipulability Ellipsoid (RME) denotes a distribution of each link velocity produced by joint angular velocity. This paper shows new index of Dynamic Reconfiguration Manipulability (DRM) combined dynamic manipulability and reconfiguration manipulability, and we have adopted the DRM to a humanoid robot, exhibiting how the DRM indicates directly the configuration-changeability of walking humanoid robot.**

I. Introduction

As for walking control of the humanoid, ZMP-based walking is known as the most promising approach, which has been proved to be a realistic control strategy to demonstrate stable walking of actual biped robots, since it can guarantee that the robots can keep standing by retaining the ZMP within the convex hull of supporting area [1], [2].

Given as an example that heel be detached from ground during its toe being contacting, a new state variable describing rotation of foot would emerge, resulting in an increase of a number of state variables. In fact, this kind of dynamics with the dimension number of state variables being changed by the result of its dynamical transitions are out of the arena of control theory that discusses how to control a system with fixed number of states. Additionally, toe-off motion has been called as non-holonomic dynamics that includes a joint without inputting torque, i.e., free joint. Meanwhile, landing of heel or toe to ground means a geometrical contact. Nakamura [7] discussed how to represent contacting motions with environment along with the dynamical equation of motion and applied it to human figures. Considering that the bipedal walking dynamics are inherently a system whose dimension number of states is changeable according to contacting conditions of foot to ground, we need some measure that describes consistently kinematical or dynamical ability of humanoid with regardless of the above bipedal gaits' varieties.

The humans' walking behavior looks like utilizing redundancy during executing a primary task of walking or gazing. Therefore we want to discuss about dynamical redundancy of humanoid robot in this paper, proposing dynamical reconfiguration manipulability (DRM) concept, which is a measure of how much a dynamical system can potentially produce a motion in a workspace with normalized input torque, by combining the dynamic manipulability [12] with reconfiguration manipulability [13]. This new measure represents how much the dynamical system of robots possesses shape-reconfiguration acceleration ability in workspace by unit torque input for all joints during executing primary tasks. The DRM have been applied to a humanoid robot, whose prior task be allocated to sustain head position or posture to be close to desired it as much as possible. The concept is shown in Fig. 1(b) and the dynamic reconfiguration manipulability ellipsoid (DRME) of floor-fixed four link robot is shown in Fig. 1(a), and we call ellipsoid as including ellipse and line segment in this paper. Simulations show the DRME varies with the human's waist position, suggesting that strategies can be applicable such as the whole configuration control can be modified through DRME based on requirement of secondary task other than walking.

Walking on uneven ground is shown in Fig. 2. Considering

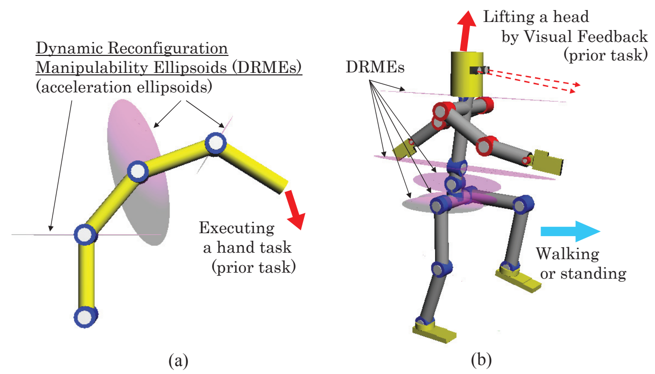

Fig. 1. Applications of dynamic reconfiguration manipulability for (a) redundant manipulator and (b) humanoid robot.

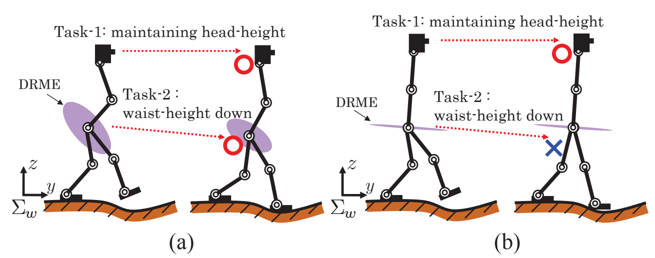

Fig. 2. Walking on uneven ground with (a) no-singular configuration has a redundant ability to accelerate the waist position during keeping head pose and reading the foot to the uneven ground (b) partially singular configuration (from waist to head) cannot afford to keep the current head pose, during reaching the foot to ground. This result can be seen by the DRME yet having the width in z-axis and the shape is flat.

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condition of task-1 (maintaining head-height) and task-2 (lowering waist-height) is given. These tasks assume that humanoid's face and eyes should be directed to recognize some object during walking on the uneven ground. There is room for z-acceleration of waist in (a), leaving a leeway for achieving task-1 and task-2 simultaneously. However, there is little room for z-acceleration of waist in (b), task-1 can be achieved but task-2 cannot be achieved since head will descend when the foot extended to ground. This means, DRM can be applied for a measure to evaluate affordability of plural tasks of humanoid walking.

II. Dynamic Reconfiguration Manipulability

A. Dynamic Manipulability

In general, equation of motion for serial link manipulators is written as

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{D}\dot{\boldsymbol{q}} = \boldsymbol{\tau} \tag{1}$$

where $\boldsymbol{M}(\boldsymbol{q}) \in \mathrm{R}^{n\times n}$ is inertia matrix, $\boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \in \mathrm{R}^n$ and $\boldsymbol{g}(\boldsymbol{q}) \in \mathrm{R}^n$ are vectors which indicate Coriolis force, centrifugal force and gravity, $\boldsymbol{D} = \mathrm{diag}[d_1, d_2, \cdots, d_n]$ is matrix which means coefficients of joints' viscous friction and $\boldsymbol{\tau} \in \mathrm{R}^n$ is joint torque. The kinematic equation of a robot, the relation of the i-th link's velocity $\dot{\boldsymbol{r}}_i \in \mathrm{R}^m$ to the angular velocity $\dot{\boldsymbol{q}} \in \mathrm{R}^n$ is represented by

$$\dot{\boldsymbol{r}}_i = \boldsymbol{J}_i\dot{\boldsymbol{q}} \quad (i = 1, 2, \cdots, n) \tag{2}$$

Then, $\boldsymbol{J}_i \in \mathrm{R}^{m\times n}$ can be described as Jacobian matrix with zero block matrix, $\boldsymbol{J}_i = [\tilde{\boldsymbol{J}}_i,\ \boldsymbol{0}]$. By differentiating Eq. (2), we can obtain the following equation.

$$\ddot{\boldsymbol{r}}_i = \boldsymbol{J}_i(\boldsymbol{q})\ddot{\boldsymbol{q}} + \dot{\boldsymbol{J}}_i(\boldsymbol{q})\dot{\boldsymbol{q}} \tag{3}$$

where we can understand that $\dot{\boldsymbol{J}}_i(\boldsymbol{q})\dot{\boldsymbol{q}}$ is the acceleration as Coliolis and centrifugal acceleration resulted from nonlinear relation of two-coordinates-space represented by $\boldsymbol{q}_i$ to $\boldsymbol{r}_i$. Then, from Eqs. (1) and (3) we can obtain the following equation.

$$\ddot{\boldsymbol{r}}_i - \dot{\boldsymbol{J}}_i(\boldsymbol{q})\dot{\boldsymbol{q}} = \boldsymbol{J}_i\boldsymbol{M}^{-1}[\boldsymbol{\tau} - \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) - \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{D}\dot{\boldsymbol{q}}] \tag{4}$$

Here, two variables are defined as follows:

$$\tilde{\boldsymbol{\tau}} \triangleq \boldsymbol{\tau} - \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) - \boldsymbol{g}(\boldsymbol{q}) - \boldsymbol{D}\dot{\boldsymbol{q}} \tag{5}$$

$$\ddot{\tilde{\boldsymbol{r}}}_i \triangleq \ddot{\boldsymbol{r}}_i - \dot{\boldsymbol{J}}_i(\boldsymbol{q})\dot{\boldsymbol{q}} = \boldsymbol{J}_i(\boldsymbol{q})\ddot{\boldsymbol{q}} \tag{6}$$

Then, Eq. (4) can be rewritten as

$$\ddot{\tilde{\boldsymbol{r}}}_i = \boldsymbol{J}_i\boldsymbol{M}^{-1}\tilde{\boldsymbol{\tau}} \quad (i = 1, 2, \cdots, n) \tag{7}$$

Considering desired accelerations $\ddot{\tilde{\boldsymbol{r}}}_{i\mathrm{d}}$ of all links yielded by a set of joint torques $\tilde{\boldsymbol{\tau}}$ that satisfies an Euclidean norm condition, that is, $\|\tilde{\boldsymbol{\tau}}\| = (\tilde{\tau}_1^2 + \tilde{\tau}_2^2 + \cdots + \tilde{\tau}_n^2)^{1/2} \leq 1$, then the each tip acceleration shapes an ellipsoid in range space of $\boldsymbol{J}_i$. These ellipsoids of each link have been known as "Dynamic Manipulability Ellipsoid (DME)" [12] (Fig.3(a)) which are described as

$$\ddot{\tilde{\boldsymbol{r}}}_{i\mathrm{d}}{}^{\mathrm{T}}[\boldsymbol{J}_i(\boldsymbol{M}^{\mathrm{T}}\boldsymbol{M})^{-1}\boldsymbol{J}_i^{\mathrm{T}}]^{+}\ddot{\tilde{\boldsymbol{r}}}_{i\mathrm{d}} \leq 1, \text{ and } \ddot{\tilde{\boldsymbol{r}}}_{i\mathrm{d}} \in \mathrm{R}(\boldsymbol{J}_i) \tag{8}$$

where, $\mathrm{R}(\boldsymbol{J}_i)$ represents range space of $\boldsymbol{J}_i$.

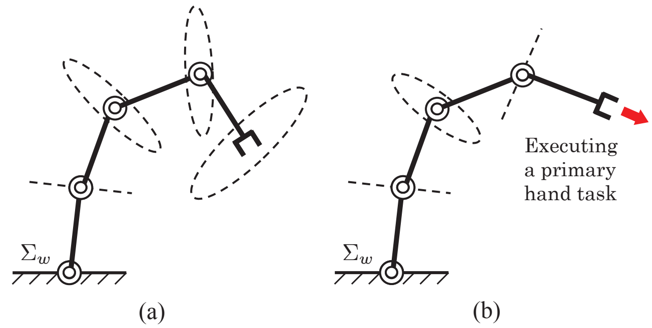


Fig. 3. (a) Dynamic manipulability ellipsoids (DMEs) represent the possible accelerations for each link with no prior task and (b) dynamic reconfiguration manipulability ellipsoids (DRMEs) represent the possible accelerations for intermediate links during the system executing primary task.

B. Dynamic Reconfiguration Manipulability

Here we assume that the desired end-effector's acceleration $\ddot{\boldsymbol{r}}_{n\mathrm{d}}$ are given as primary task. Relation between $\ddot{\tilde{\boldsymbol{r}}}_n$ and $\tilde{\boldsymbol{\tau}}$ is denoted to give $i = n$ into Eq. (7), then,

$$\ddot{\tilde{\boldsymbol{r}}}_n = \boldsymbol{J}_n\boldsymbol{M}^{-1}\tilde{\boldsymbol{\tau}} \tag{9}$$

Solving Eq. (9) for $\tilde{\boldsymbol{\tau}}$ yielding desired acceleration $\ddot{\tilde{\boldsymbol{r}}}_{n\mathrm{d}}$

$$\begin{aligned}\tilde{\boldsymbol{\tau}} = {} & (\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}\ddot{\tilde{\boldsymbol{r}}}_{n\mathrm{d}} \\ & + [\boldsymbol{I}_n - (\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}(\boldsymbol{J}_n\boldsymbol{M}^{-1})]\,{}^1\boldsymbol{l}\end{aligned} \tag{10}$$

${}^1\boldsymbol{l}$ is an arbitrary vector satisfying ${}^1\boldsymbol{l} \in \mathrm{R}^n$. The left superscript "1" of ${}^1\boldsymbol{l}$ means the first dynamic reconfiguration task. In the right side of Eq. (10), the first term denotes the solution making $\tilde{\boldsymbol{\tau}}$ minimize in the null space of $\boldsymbol{J}_n\boldsymbol{M}^{-1}$ during implementing $\ddot{\tilde{\boldsymbol{r}}}_{n\mathrm{d}}$. The second term denotes the components of torques at each joint, which can change the shape of manipulator regardless with the influence of $\ddot{\tilde{\boldsymbol{r}}}_{n\mathrm{d}}$ given arbitrarily as end-effector acceleration for tracking the desired trajectory.

Providing the first dynamic reconfiguration task, that is the first reconfiguration task ${}^1\ddot{\tilde{\boldsymbol{r}}}_{j\mathrm{d}}$ $(j = 1, 2, \cdots, n-1)$, is given to the j-th link, shall we discuss realizability of ${}^1\ddot{\boldsymbol{r}}_{j\mathrm{d}}$ in the following argument. In this research, ${}^1\ddot{\boldsymbol{r}}_{j\mathrm{d}}$ is assumed to be commanded by an dynamic reconfiguration control system of higher level. We can obtain the relation of ${}^1\ddot{\tilde{\boldsymbol{r}}}_j$ and $\ddot{\tilde{\boldsymbol{r}}}_{n\mathrm{d}}$ from Eqs. (7) and (10).

$$\begin{aligned}{}^1\ddot{\tilde{\boldsymbol{r}}}_j = {} & \boldsymbol{J}_j\boldsymbol{M}^{-1}(\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}\ddot{\tilde{\boldsymbol{r}}}_{n\mathrm{d}} \\ & + \boldsymbol{J}_j\boldsymbol{M}^{-1}[\boldsymbol{I}_n - (\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}(\boldsymbol{J}_n\boldsymbol{M}^{-1})]\,{}^1\boldsymbol{l}\end{aligned} \tag{11}$$

Then, noticing the relation of Eq. (6),

$$\begin{aligned}& {}^1\ddot{\boldsymbol{r}}_j - \dot{\boldsymbol{J}}_j\dot{\boldsymbol{q}} - \boldsymbol{J}_j\boldsymbol{M}^{-1}(\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}(\ddot{\boldsymbol{r}}_{n\mathrm{d}} - \dot{\boldsymbol{J}}_n\dot{\boldsymbol{q}}) \\ & \quad = \boldsymbol{J}_j\boldsymbol{M}^{-1}[\boldsymbol{I}_n - (\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}(\boldsymbol{J}_n\boldsymbol{M}^{-1})]\,{}^1\boldsymbol{l}\end{aligned} \tag{12}$$

Here, we define three variables shown as

$${}^1\ddot{\hat{\boldsymbol{r}}}_j \triangleq \dot{\boldsymbol{J}}_j\dot{\boldsymbol{q}} + \boldsymbol{J}_j\boldsymbol{M}^{-1}(\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}(\ddot{\boldsymbol{r}}_{n\mathrm{d}} - \dot{\boldsymbol{J}}_n\dot{\boldsymbol{q}}) \tag{13}$$

$$\Delta\,{}^1\ddot{\boldsymbol{r}}_j \triangleq {}^1\ddot{\boldsymbol{r}}_j - {}^1\ddot{\hat{\boldsymbol{r}}}_j \tag{14}$$

$${}^1\boldsymbol{\Lambda}_j \triangleq \boldsymbol{J}_j\boldsymbol{M}^{-1}[\boldsymbol{I}_n - (\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}(\boldsymbol{J}_n\boldsymbol{M}^{-1})] \tag{15}$$

In Eq. (13), ${}^1\ddot{\hat{\boldsymbol{r}}}_j$ is represents acceleration caused by manipulator's shape change. In the right side of Eq. (13), the

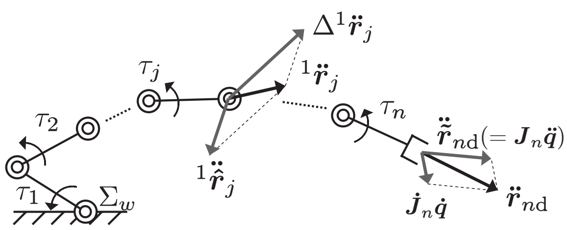


Fig. 4. Reconfiguration during hand executing task $\ddot{\boldsymbol{r}}_{nd}$. $\boldsymbol{J}_j\boldsymbol{M}^{-1}(\boldsymbol{J}_n\boldsymbol{M}^{-1})^{+}\ddot{\tilde{\boldsymbol{r}}}_{nd}$ is a induced acceleration of j-th link by $\ddot{\tilde{\boldsymbol{r}}}_{nd}$. When $\Delta^1\ddot{\boldsymbol{r}}_j$ is produced through $^1\boldsymbol{l}$, $^1\ddot{\boldsymbol{r}}_j$ appears at j-th link, meaning avoiding acceleration can be achieved as a secondary task.

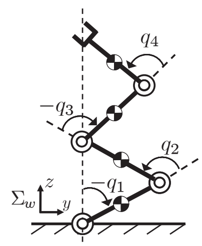
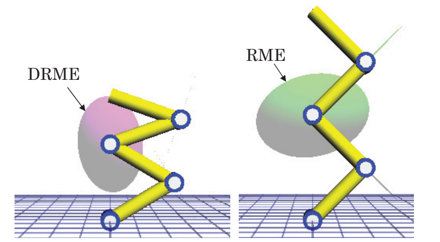
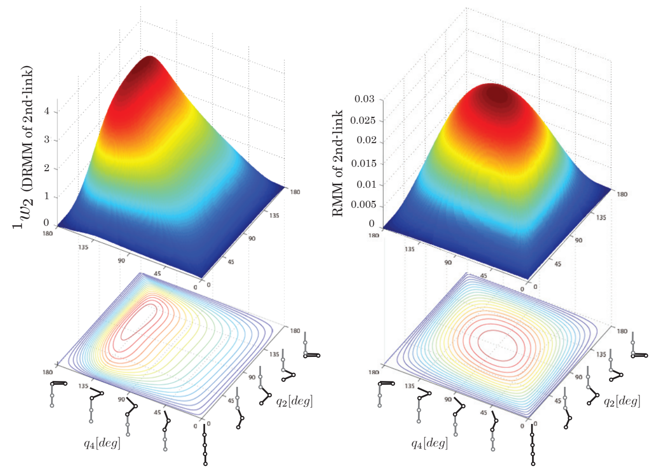


Fig. 5. 4-link manipulator.



(a) (b)

Fig. 6. Shapes of manipulator : which have (a) peak of $^1w_2$ in Fig. 7(a) with DRME and (b) peak of 2nd-link RMM in Fig. 7(b) with RME.



(a) (b)

Fig. 7. $^1w_2$ (dynamic reconfiguration manipulability measure of 2nd-link) and reconfiguration manipulability measure (RMM) [14] of 2nd-link to vertical motion.

first term denotes Coliolis and centrifugal acceleration of j-th link, the second term represents influence of $^1\ddot{\tilde{\boldsymbol{r}}}_{nd}$ on j-th link except Coliolis and centrifugal acceleration at n-th link. Then, Eq. (12) can be rewritten as

$$\Delta^1\ddot{\boldsymbol{r}}_j = {}^1\boldsymbol{\Lambda}_j\,{}^1\boldsymbol{l} \tag{16}$$

The relation between $^1\ddot{\boldsymbol{r}}_j$ and $\Delta^1\ddot{\boldsymbol{r}}_j$ is shown in Fig. 4. However, the problem is whether we can yield desired $\Delta^1\ddot{\boldsymbol{r}}_{jd}$, that is, whether we can find $^1\boldsymbol{l}$ to generate $\Delta^1\ddot{\boldsymbol{r}}_{jd}$. From Eq. (16), we can obtain $^1\boldsymbol{l}$ as

$$^1\boldsymbol{l} = {}^1\boldsymbol{\Lambda}_j^{+}\Delta^1\ddot{\boldsymbol{r}}_{jd} + (\boldsymbol{I}_n - {}^1\boldsymbol{\Lambda}_j^{+}\,{}^1\boldsymbol{\Lambda}_j)\,{}^2\boldsymbol{l} \tag{17}$$

In Eq. (17), $^2\boldsymbol{l}$ is an arbitrary vector satisfying $^2\boldsymbol{l} \in \mathrm{R}^n$. Assuming that $^1\boldsymbol{l}$ is restricted as $\|^1\boldsymbol{l}\| \leq 1$, then we obtain next relation,

$$(\Delta^1\ddot{\boldsymbol{r}}_{jd})^{\mathrm{T}}({}^1\boldsymbol{\Lambda}_j^{+})^{\mathrm{T}1}\boldsymbol{\Lambda}_j^{+}\Delta^1\ddot{\boldsymbol{r}}_{jd} \leq 1 \tag{18}$$

If $\mathrm{rank}({}^1\boldsymbol{\Lambda}_j) = m$, Eq. (18) represents an ellipsoid expanding in m-dimensional space, holding

$$\Delta^1\ddot{\boldsymbol{r}}_{jd} = {}^1\boldsymbol{\Lambda}_j{}^1\boldsymbol{\Lambda}_j^{+}\Delta^1\ddot{\boldsymbol{r}}_{jd}, \qquad \Delta^1\ddot{\boldsymbol{r}}_{jd} \in \mathrm{R}^m \tag{19}$$

which indicates that $\Delta^1\ddot{\boldsymbol{r}}_{jd}$ can be arbitrarily generated in m-dimensional space and Eq. (16) always has the solution $^1\boldsymbol{l}$ corresponding to all $\Delta^1\ddot{\boldsymbol{r}}_{jd} \in \mathrm{R}^m$. On the other hand, if $\mathrm{rank}({}^1\boldsymbol{\Lambda}_j) = r < m$, $\Delta\ddot{\boldsymbol{r}}_{jd}$ does not value arbitrarily in R^m. In this case, reduced $\Delta\ddot{\boldsymbol{r}}_{jd}$ is denoted as $\Delta^1\ddot{\boldsymbol{r}}^*_{jd}$. Then Eq. (18) is written as

$$\begin{aligned}(\Delta^1\ddot{\boldsymbol{r}}^*_{jd})^{\mathrm{T}}({}^1\boldsymbol{\Lambda}_j^{+})^{\mathrm{T}}\,{}^1\boldsymbol{\Lambda}_j^{+}\Delta^1\ddot{\boldsymbol{r}}^*_{jd} \leq 1\\ (\Delta^1\ddot{\boldsymbol{r}}^*_{jd} = {}^1\boldsymbol{\Lambda}_j{}^1\boldsymbol{\Lambda}_j^{+}\Delta^1\ddot{\boldsymbol{r}}_{jd})\end{aligned} \tag{20}$$

Equation (20) describes an ellipsoid expanded in r-dimensional space. These ellipsoids of Eqs. (18) and (20) are shown in Fig.3(b).

C. Dynamic Reconfiguration Manipulability Shape Index(DRMSI)

In this section, we propose the index evaluating DRM. Thus, by applying the singular value decomposition for this matrix $\boldsymbol{\Lambda}$, we get

$$^1\boldsymbol{\Lambda}_j = {}^1\boldsymbol{U}_j^1\boldsymbol{\Sigma}_j^1\boldsymbol{V}_j^{\mathrm{T}} \tag{21}$$

$$^1\boldsymbol{\Sigma}_j = \begin{array}{c c} & \begin{array}{cc} r & n-r \end{array} \\ \begin{array}{c} r \\ \\ m-r \end{array} & \begin{bmatrix} {}^1\sigma_{j,1} & & \boldsymbol{0} & \\ & \ddots & & \boldsymbol{0} \\ \boldsymbol{0} & & {}^1\sigma_{j,r} & \\ & \boldsymbol{0} & & \boldsymbol{0} \end{bmatrix} \end{array} \tag{22}$$

In Eqs. (21) and (22), $^1\boldsymbol{U} \in \mathrm{R}^{m\times m}, {}^1\boldsymbol{V} \in \mathrm{R}^{n\times n}$ are orthogonal matrixes, and r denotes the number of non-zero singular values of $^1\boldsymbol{\Lambda}_j$ and $\sigma_{j,1}\geq \cdots \geq\sigma_{j,r} > 0$. In addition, $r\leq m$ because $\mathrm{rank}({}^1\boldsymbol{\Lambda}_j)\leq m$. So, dynamic reconfiguration capability of j-th link when hand of manipulator operating task can be described by following equation.

$$^1w_j = {}^1\sigma_{j,1}\cdot{}^1\sigma_{j,2}\cdots{}^1\sigma_{j,r} \tag{23}$$

In this paper, we defined the value of w_j in Eq. (23) as dynamic reconfiguration manipulability measure (DRMM), which indicates the degree of that reconfiguration acceleration of j-th link can be generated for arbitrary direction. And, volume of dynamic reconfiguration ellipsoid at the j-th link is described as $^1V_{\mathrm{DR}j}$. Then, in order to consider dynamic reconfiguration measure of the whole manipulator-links, we define a index named dynamic reconfiguration manipulability shape index (DRMSI) as follows:

$$^1W_{\mathrm{DR}} = \sum_{j=1}^{n-1} a_j\,{}^1V_{\mathrm{DR}j} \tag{24}$$

Here, a_j is unit adjustment between different dimension. In this paper, singular-values increase a hundredfold to enlarge value of ellipsoid, compared to ellipse or line segment.

D. Numerical Examples

In this section, we introduce a numerical example of the proposed DRM for posture of a 4-link manipulator in Fig. 5.

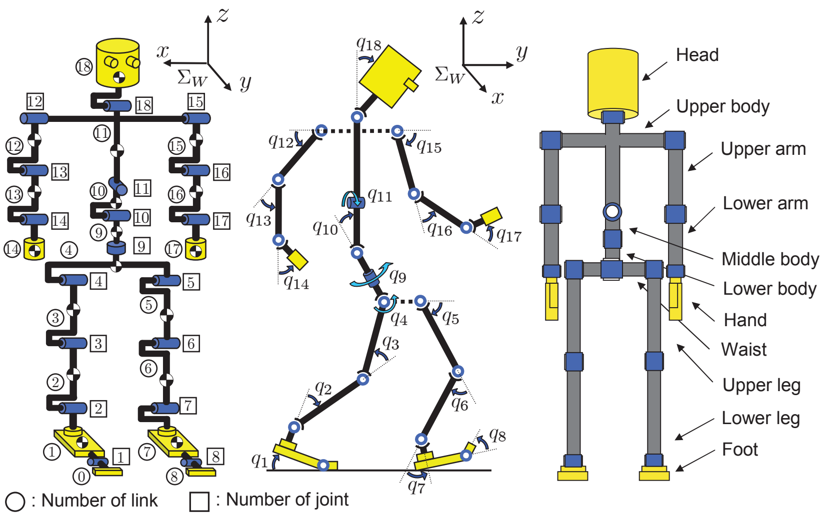


Fig. 8. Definition of humanoid's link, joint and angle number.

TABLE I

PHYSICAL PARAMETERS

Link	l_i	m_i	d_i
Head	0.24	4.5	0.5
Upper body	0.41	21.5	10.0
Middle body	0.1	2.0	10.0
Lower body	0.1	2.0	10.0
Upper arm	0.31	2.3	0.03
Lower arm	0.24	1.4	1.0
Hand	0.18	0.4	2.0
Waist	0.27	2.0	10.0
Upper leg	0.38	7.3	10.0
Lower leg	0.40	3.4	10.0
Foot	0.07	1.1	10.0
Total	1.7	63.8	

Length, mass and coefficient of viscous friction of each link and joint are set to be 0.3[m], 1.0[kg], and 2.0[N·m·s/rad]. In this simulation, we assume that tip of link-2 and link-4 are always placed $y = 0$, that is, when q_2 and q_4 are given, q_1 and q_3 are set as $q_1 = -q_2/2.0$ and $q_3 = -(q_2 + q_4)/2.0$. Figure 6(a) and (b) depict the DRME (scaled) and RME (scaled) with manipulator shapes, which indicate the peak of 2nd-link-DRMM distribution and 2nd-link reconfiguration manipulability measure (RMM) distribution shown in Fig. 7. In Fig. 7, the peak of 2nd-link RMM at $q_2 = 90°$ and $q_4 = 90°$. On the other hand, the peak of 2nd-link DRMM at $q_2 = 118°$ and $q_4 = 141°$. Difference of the results is caused from considering dynamical peculiarities or not.

III. Dynamical Walking Model

We discuss a biped robot whose definition is depicted in Fig. 8. Table I indicates length l_i [m], mass m_i [kg] of links and joints' coefficient of viscous friction d_i [N·m·s/rad], which are decided based on [8]. Our model represents rigid whole body—feet including toe, torso, arms and body—having 18 degree-of-freedom. Detail explanation of this model is omitted, which is described in [9].

IV. Visual Lifting Approach

A. Feedback lifting torque generator

This section presents a vision-feedback control for improving humanoid's standing/walking stability [10] as shown in Fig. 9. Here, the force exerted on the head to minimize $\delta\boldsymbol{\psi}(t) = \boldsymbol{\psi}_{\rm d}(t) - \boldsymbol{\psi}(t)$ calculated from measured position or pose, we assume this parameter as being detected correctly in this paper. The joint torque $\boldsymbol{\tau}_{\rm h}(t)$ that pulls the robot's head up is given the following equation:

$$\boldsymbol{\tau}_{\rm h}(t) = \boldsymbol{J}_{\rm h}(\boldsymbol{q})^{\rm T}\boldsymbol{K}_{\rm p}\delta\boldsymbol{\psi}(t) \tag{25}$$

where $\boldsymbol{J}_{\rm h}(\boldsymbol{q})$ in Fig. 9 is Jacobian matrix of the head pose against joint angles including $q_1, q_2, q_3, q_4, q_9, q_{10}, q_{11}, q_{18}$, and $\boldsymbol{K}_{\rm p}$ means proportional gain similar to impedance control. We use this input to compensate the falling motions caused by gravity or dangerous slipping motion happened unpredictably during all walking states in Fig. 10.

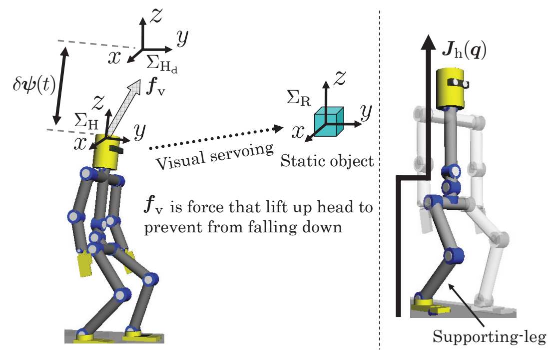


Fig. 9. Concept of Visual-Lifting Approach.

B. Feedforward leg and body motion generator

In addition to $\boldsymbol{\tau}_{\rm h}(t)$, we used two input torques: $\boldsymbol{\tau}_{\rm t}(t) = [0, \cdots, 0, \tau_{\rm t5}, 0, \cdots, 0]^{\rm T}$ to make floating-leg (joint-5) step forward and $\boldsymbol{\tau}_{\rm w}(t) = [0, \cdots, 0, \tau_{\rm w11}, 0, \cdots, 0]^{\rm T}$ to swing waist's roll angle (joint-11) according to supporting-foot. The element $\tau_{\rm t5}$ and $\tau_{\rm w11}$ of $\boldsymbol{\tau}_{\rm t}(t)$ and $\boldsymbol{\tau}_{\rm w}(t)$ are settled by approximate human's walking-cycle as below:

$$\tau_{\rm t5} = 20\cos\left[2\pi(t - t_1)/1.85\right] \tag{26}$$

$$\tau_{\rm w11} = \begin{cases} 50\sin\left[2\pi(t - t_1)/1.85\right] & (if \text{ Right leg}) \\ -50\sin\left[2\pi(t - t_1)/1.85\right] & (if \text{ Left leg}) \end{cases} \tag{27}$$

which are chosen by empirical prenary simulations to find out appropoate inputs making walking motion fall into stable limit cycle, i.e., stable walking. Here, t_1 means the time that supporting-foot and contacting-foot are switched, which is gate-transition from (V′) and (VII′) to (VII).

C. Combined lifting/swinging controller

Combining three torque generators expressed as Eqs. (25), (26) and (27), a controller for walking is created as $\boldsymbol{\tau}(t) = \boldsymbol{\tau}_{\rm h}(t) + \boldsymbol{\tau}_{\rm t}(t) + \boldsymbol{\tau}_{\rm w}(t)$.

V. Example of Bipedal Walking

Under the environment that sampling time was set as 3.0×10^{-3} [sec] and friction force between foot and the ground as $f_{\rm t} = 0.7 f_{\rm n_z}$, the following simulations were conducted.

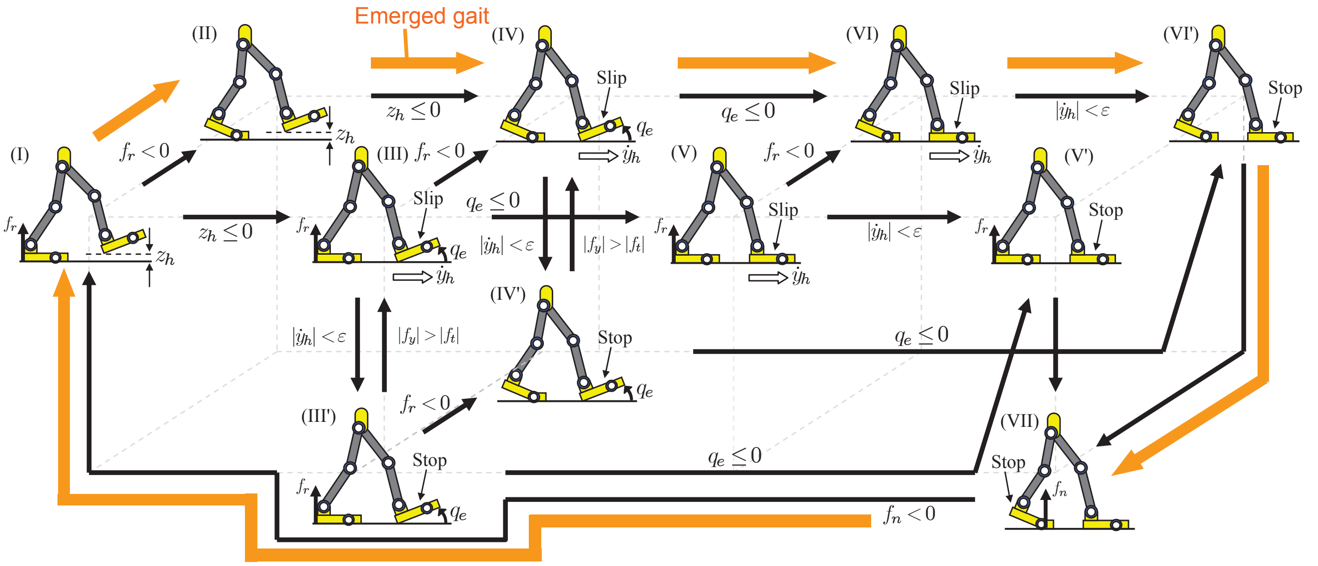


Fig. 10. State, gait's transition and emerged walking gait.

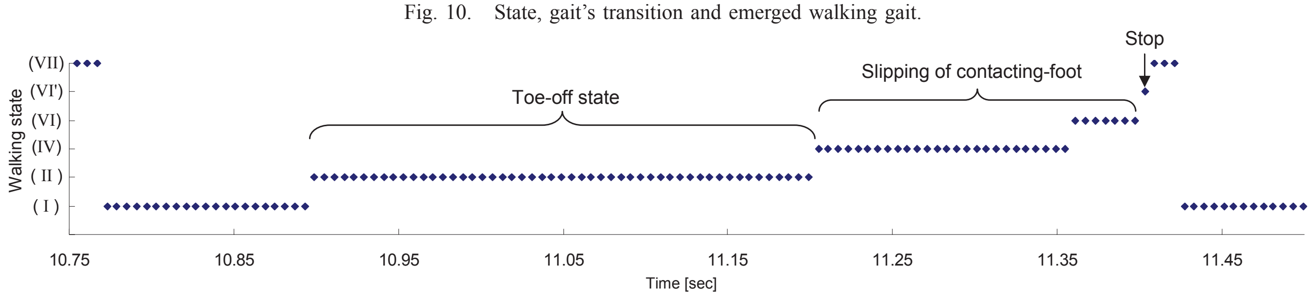


Fig. 11. State transition of walking in one step.

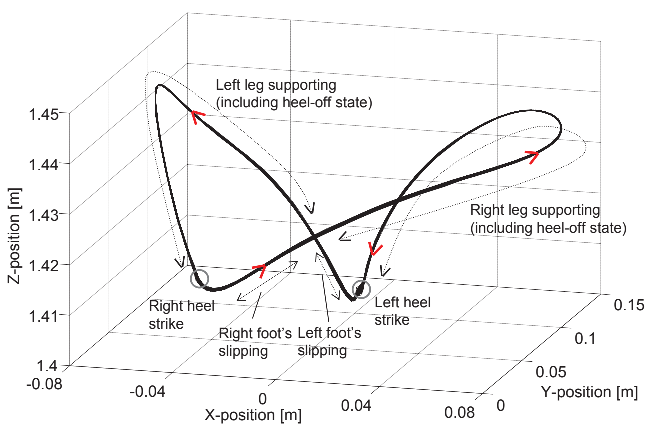


Fig. 12. Emerged limit cycle $[(x, y, z)$ trajectory of neck$]$

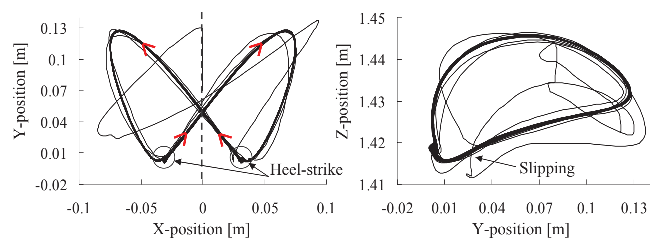


Fig. 13. Motion trajectory of neck.

A. Stable Walking by Visual-Lifting Approach

In this section, we set lifting proportional gain $\boldsymbol{K}_{\mathrm{p}} = \mathrm{diag}[20, 290, 1100]$ to achieve stable walking. Followings are the results: average length of stride is 0.43 [m] and walking speed is 2.15 [km/h]. Figure 11 show state transition generated by the humanoid's dynamics. In this simulation, the humanoid walked in accordance with the following path: (I) $\rightarrow$ (II) $\rightarrow$ (IV) $\rightarrow$ (VI) $\rightarrow$ (VI$'$) $\rightarrow$ (VII) $\rightarrow$ (I) $\rightarrow \cdots$ in Fig. 10 as "Emerged gait." This transition was selected among all possible transient in Fig. 10 by the closed loop dynamics. Figure 12 depicts trajectory of neck (origin of link-18) in 3-D space representation, excluding a trajectory in transient state corresponding to 0–20 steps, this means that the walking motion converged into limit cycle after 21 walking steps. Then, the trajectories that are separated into two plane (x-y plane and y-z plane) from initial condition to 200 steps are shown in Fig. 13. We can confirm that motion concerning left side and right side against the dotted line is symmetric, which means the neck and shoulder swung along with y-axis given at Fig. 13, representing rolling motion of upper body. The right graph representing neck's motion in y-z plane, the neck swayed in sagittal plane forward and backward with height varying by walking states including heel-striking state in it. These figures implies that visual feedback has stabilized the walking including gait's transition and motions as shown in Fig. 10, including toe-off state, heel-striking, slipping and change of state variables.

B. Analyses based on Dynamic Reconfiguration Manipulability

In this section, three kinds of lifting proportional-gain are set to be $\boldsymbol{K}_{\mathrm{p}} = \mathrm{diag}[20, 290, 1100]$ (Large lifting-gain), $\boldsymbol{K}_{\mathrm{p}} = \mathrm{diag}[20, 290, 950]$ (Medium lifting-gain) and $\boldsymbol{K}_{\mathrm{p}} =$

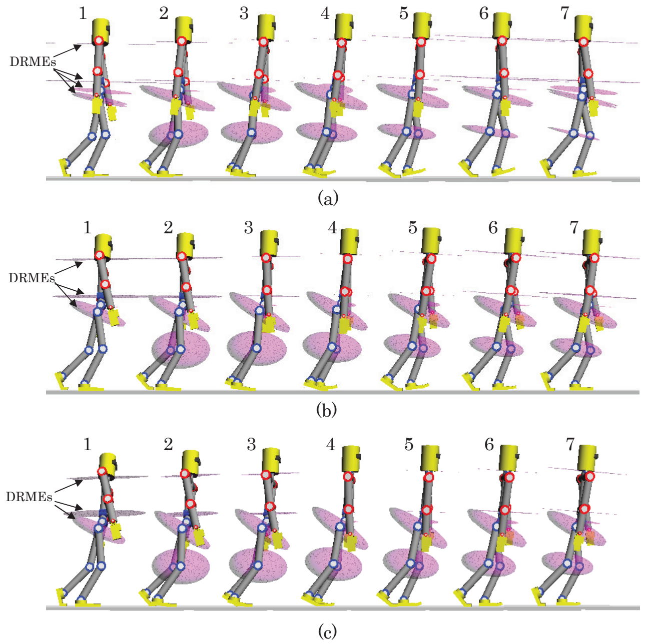


Fig. 14. Screen-shot of bipedal walking with DRMEs by different gain set : (a) Large Lifting Gain $\boldsymbol{K}_{\rm p} = {\rm diag}[20, 290, 1100]$ (b) Medium lifting-gain $\boldsymbol{K}_{\rm p} = {\rm diag}[20, 290, 950]$ (c) Small lifting-gain $\boldsymbol{K}_{\rm p} = {\rm diag}[20, 290, 900]$.

${\rm diag}[20, 290, 900]$ (Small lifting-gain) to compare walkings by DRM. The humanoid walked as shown Fig. 14(a), (b) and (c), respectively. Then, there are no DRMEs (exactly line segments existing) at knee of (a)-1, (b)-1 and (c)-1, since supporting-foot is surface-contacting, that is, joint angles $\boldsymbol{q} = [q_2, q_3, \cdots, q_{18}]^{\rm T}$. On the other hand, there are DRMEs (ellipses) at knee of the other phases, since supporting-foot is point-contacting, that is, joint angles $\boldsymbol{q} = [q_1, q_2, \cdots, q_{18}]^{\rm T}$. In Fig. 14, shapes of (c) crouches down, compared to (a). Furthermore, DRMEs volume of (c) is larger than (a). In Figs. 15 and 16, as lifting gain larger, DRMSI representing whole volume of DRMEs is smaller. This means walking of (c) has higher shape-changeability than (a), but it seems that walking of (c) is far from human's walking. And if assuming model including passive joint at toe, DRM can be applied only in time S^* which means supporting-foot is surface contacting that is when ZMP is kept inside convex hull of supporting area. In other wards, it is possible to estimate robots' shape-changeability in time S^* even if assuming as that model.

VI. Conclusion

In this paper, we propose a new index for dynamic ability to change configuration as a subsegment redundancy utilization, named Dynamic Reconfiguration Manipulability (DRM), and demonstrate the manipulability with numerical examples for a 4-link manipulator and a humanoid robot. In addition, we introduced Lifting Approach which grantees to keep the posture of humanoid robot stable. And, we confirmed that the robot with walking shape of crouching down has higher dynamic ability to change configuration than walking shape of stretching humanoid's leg, which can be hopefully used for adaptation for uneven surface of ground.

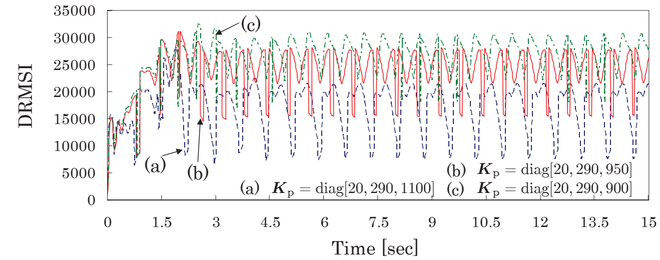


Fig. 15. DRMSI until $t = 15.0[s]$.

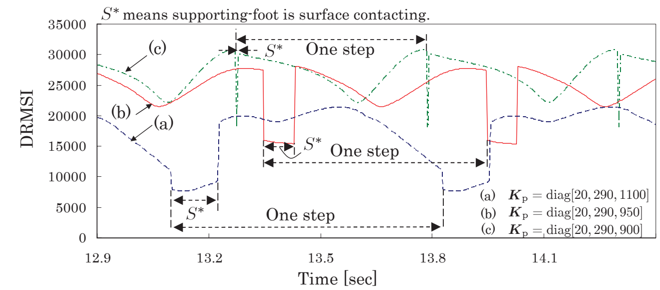


Fig. 16. DRMSI around $t = 13.5[s]$.

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