

FORCE CONTROL OF LINK SYSTEMS USING THE PARALLEL SOLUTION SCHEME

Daigoro Isobe

Graduate School of Systems and Information Engineering, University of Tsukuba
1-1-1 Tennodai Tsukuba-shi, Ibaraki 305-8573, Japan
isobe@kz.tsukuba.ac.jp

Shunsuke Sato

Nissan Motor Co., Ltd.
6-17-1 Ginza Chuo-ku, Tokyo 104-8023, Japan

Abstract

In this paper, force control of link systems considering dynamical effects is carried out by using the parallel solution scheme, which was previously proposed and successfully applied to inverse dynamics calculations of flexible manipulators. Generally, inverse dynamics is calculated by using dynamic equations, and control torque for generated forces is calculated by using Jacobian matrices derived from kinematic equations. Two different sets of torque are summed in such cases. On the other hand, the parallel solution scheme calculates both types of torque in a single procedure, without using Jacobian matrices. The calculation is enabled by solving the equation of motion in the dimension of force, and by formulating the relationship between the calculated forces and joint torque in a matrix form, separated into terms of different parameters. Generated forces for the control can be considered simply by adding the values into one of the components in the equation, which is used for calculating inverse dynamics. The validity of the scheme is verified, in this paper, by carrying out a force control experiment on a simple link system where both generated forces and dynamical effects should be considered.

Key Words

Force Control, Inverse Dynamics, Link Systems, Parallel Solution Scheme

1. Introduction

Recent developments in robotics have increased the requirements for mobility of robots as well as complexity in their tasks. One of the ways to maintain the stability of quick motion tasks is to consider the dynamics compensation by using dynamic equations. However, the generally used dynamic equations include variables that are interdependent between the constituting links, since they are evaluated in relative polar coordinates and in the

dimension of torque. Accordingly, it becomes highly complicated to derive inverse dynamics of closed kinematic chains, or structurally transforming ones. Many researchers have developed their own ways [1-3] to solve the problem, by devising and implementing new schemes to handle the dynamic equations. On the other hand, Isobe developed a completely different way [4] for calculating inverse dynamics by using a finite element approach. The scheme is named the parallel solution scheme, since it computes nodal forces in parallel by using the equations of motion expressed in the dimension of force, and converts them to torque by using a matrix-form equation separated into individual terms of nodal forces, coordinate transformation, and member length. Therefore, the scheme can naturally deal with open- and closed-loop link systems independently, as well as those that gradually transform and change their dynamics. There is also no need to revise the basic numerical algorithm of the scheme, regardless of the stiffness of the constituting link member, whether it is rigid or flexible [5].

In this paper, we will discuss such cases where force control is required, as well as the dynamic compensation of the link system. Normally, control torque for generated forces and the inverse dynamics are calculated in different approaches; the former by using Jacobian matrices derived from kinematic equations, and the latter by using the dynamic equations. On the other hand, the former torque values are calculated in the same manner and with the same algorithm for calculating inverse dynamics in the parallel solution scheme. It is possible since the scheme originally handles the mechanical behavior of link systems in the dimension of force. The parallel solution scheme handles two different sets of joint torque in a single procedure, and additional derivation of Jacobian matrices or dynamic equations is not required. The validity of the scheme is verified by carrying out a force control experiment on a quick motion, two-arm link system holding an object, where both generated forces and dynamical effects should be considered.

2. The Parallel Solution Scheme

In this section, the formerly proposed parallel solution scheme is briefly explained, by comparing the main equation for calculating inverse dynamics with that of conventional schemes. Readers should refer to papers [4] and [5] for further information. Additionally, handling of generated forces in nodal force vector is discussed, and a simple numerical example is shown.

2.1 Comparison with Schemes Using Dynamic Equations

Dynamic equations for link systems are generally derived by the Newton-Euler method or the Lagrangian method. In a summarized expression, the equations are written as

$$\{\tau\} = [M(\theta)]\{\ddot{\theta}\} + \{V(\theta, \dot{\theta})\} + \{G(\theta)\}, \quad (1)$$

where $\{\tau\}$ is the torque vector, $[M]$ the inertial force matrix, $\{V\}$ the centrifugal force and Coriolis force term vector, and $\{G\}$ the gravity force term vector. θ , $\dot{\theta}$, and $\ddot{\theta}$ within the parentheses are the relative variables of the angle, the angular velocity and the angular acceleration between each link, respectively. All of the parameters in the equation relate to each other since they are derived in relative polar coordinates and in the dimension of torque. Therefore, most parts of the equations must be revised when the structural configuration of the link system is changed.

On the other hand, torque values are calculated by using the following equation in the parallel solution scheme [4,5];

$$\{\tau^n\} = [L^n][T^n]\{P^n\}, \quad (2)$$

where $\{\tau^n\}$ is the torque vector, $\{P^n\}$ the vector related to nodal forces, $[T^n]$ the transformation matrix between global and elemental coordinates, and $[L^n]$ the member length matrix. The superscript on the upper right indicates the total number of links. The nodal forces are evaluated in an absolute Cartesian coordinate system, and in the dimension of force. The equation is completely separated into terms of different parameters, and each matrix has a clear physical meaning related to the modeled link system. The member length matrix $[L^n]$, for example, contains components in the dimension of length, which play roles in converting force to torque. Also, the configuration of the components in the matrix expresses the structural connectivity of the link system. The separation of the parameters makes the equation highly expansible and flexible, and thus the scheme becomes applicable to complex link systems without difficulty.

An incremental nodal force vector $\{\Delta f\}$, required for the link system in motion between time t and $t + \Delta t$, is

derived by the following equation;

$$\begin{aligned} \{\Delta f\} &= \{R\}_t - \{F\}_{t+} \\ [M] &\left(\frac{1}{\beta\Delta t^2}\{\Delta u\} - \frac{1}{\beta\Delta t}\{\dot{u}\}_t - \left(\frac{1}{2\beta} - 1\right)\{\ddot{u}\}_t\right), \end{aligned} \quad (3)$$

where $[M]$ is the total mass matrix, $\{F\}$ the external force vector, $\{R\}$ the internal force vector, $\{\Delta u\}$ the incremental displacement vector, $\{\dot{u}\}$ the velocity vector, and $\{\ddot{u}\}$ the acceleration vector. β is the integral parameter for Newmark's β method [6], a widely used time integration scheme. The operation distance between each incremental step calculated from a target trajectory is used as an input for $\{\Delta u\}$. The velocity and acceleration vectors can also be given directly as input data, but we used Newmark's β method ($\delta = 1/2$, $\beta = 1/4$) for calculating these values in this paper. The values of the internal force vector $\{R\}$ will all actually become zero, since the consideration of the deformation of link members in the inverse dynamics calculation process is not required. The external vector includes information such as dead loads and other additional forces acting at nodal points. Each corresponding term in the incremental nodal force vector is then substituted into Eq. (2) to constitute the vector $\{P^n\}$. Although the scheme requires incremental calculation, it has been confirmed in previous works [4,5] that the calculation time in an actual control is suppressed to a practical value.

2.2 Handling of Generated Forces in Nodal Force Vector

If the control torque for generated forces is required in addition to the dynamic compensation, the torque values should be added, in the conventional schemes, to the right hand side of Eq. (1) as follows:

$$\{\tau\} = [M(\theta)]\{\ddot{\theta}\} + \{V(\theta, \dot{\theta})\} + \{G(\theta)\} + [J]^T\{F_G\}, \quad (4)$$

where $[J]$ is the Jacobian matrix, and $\{F_G\}$ is the generated force vector. The Jacobian matrix is derived from kinematic equations, and we need to do summation of these two different sets of torque in this case.

On the other hand, the control torque for generated forces can be easily considered in the parallel solution scheme, by simply adding the generated force values to the vector related to nodal forces $\{P^n\}$, in Eq. (2). The vector gives information of the nodal forces acting on the constituting link members (see Fig. 1), and is defined as

$$\{P^n\} = \begin{Bmatrix} P_1 \\ P_2 \\ \cdot \\ \cdot \\ P_n \end{Bmatrix}, \text{ where } \{P_i\} = \begin{Bmatrix} F_{iX} \\ F_{iY} \\ F_{iZ} \\ \sum_{j=i+1}^n F_{jX} \\ \sum_{j=i+1}^n F_{jY} \\ \sum_{j=i+1}^n F_{jZ} \\ F_{i\phi X} \\ F_{i\phi Y} \\ F_{i\phi Z} \end{Bmatrix}. \quad (5)$$

Here, the subscripts i and j indicate the link numbers ($i, j = 1 \sim n$), X, Y, Z the global coordinates, and ϕ the rotational components, respectively. The 1st~3rd row components in $\{P_i\}$ are the nodal forces acting at the center of gravity, 4th~6th the sum of nodal forces acting at the tip of the i -th link member, and 7th~9th the moment of inertia acting around the center of gravity. The generated force values are added to each component in $\{P_i\}$, which can be specified in input data. Namely, there is no requirement for additional calculation of the Jacobian matrix or revision of the equation, etc., in spite of the consideration of the completely different types of torque values.

2.3 Numerical Example

A simple numerical test is carried out to verify the validity of the parallel solution scheme. A wall-trace task is given to a 2-link manipulator as shown in Fig. 2. A force value of 0.4 N is constantly generated at the tip of the manipulator against the wall. Figure 3 shows the joint torque curves of Joint 1, which are calculated for the task. The torque curve obtained from the parallel solution scheme is in perfect agreement with that from the

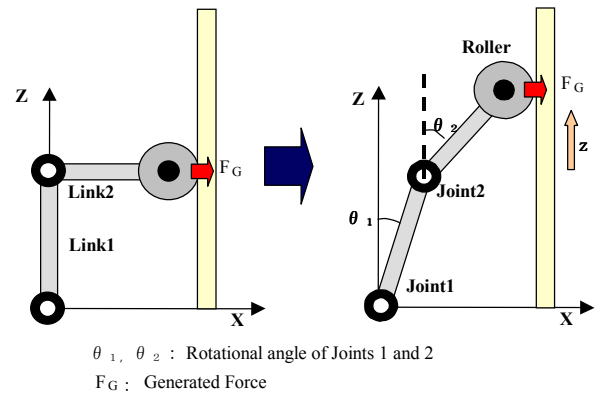


Fig. 2 A wall-trace task for a 2-link manipulator

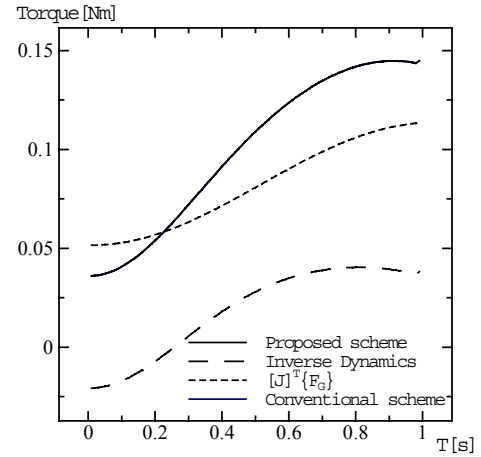


Fig. 3 Joint torque curves for the wall-trace task

conventional scheme, which is the sum of inverse dynamics and the control torque for the generated force.

3. Control Experiments

The parallel solution scheme is implemented into a force control system as shown in Fig. 4, in which the PID feedback, force feedback and feed-forward control are all combined in the design. A target trajectory based upon the Cartesian coordinates is given as an input, and control

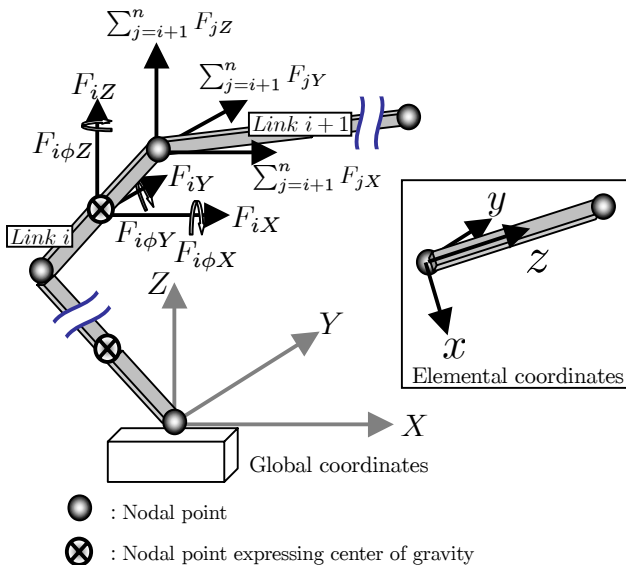


Fig. 1 Nodal forces acting on i -th link in an open-loop n -link mechanism

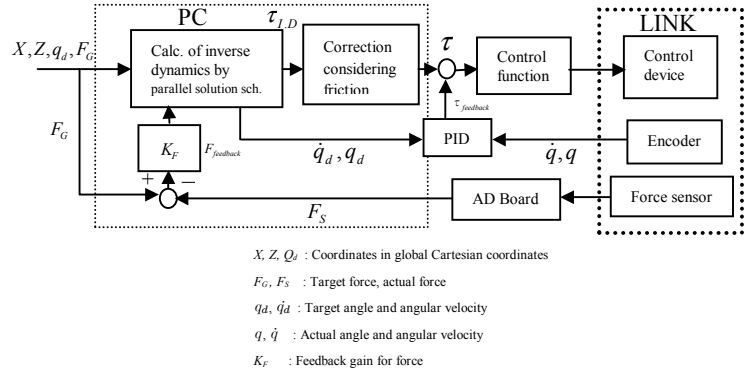


Fig. 4 Outline of the force control system

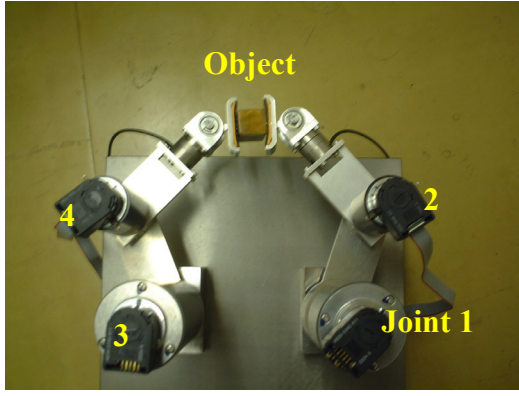


Fig. 5(a) Two manipulators holding an object

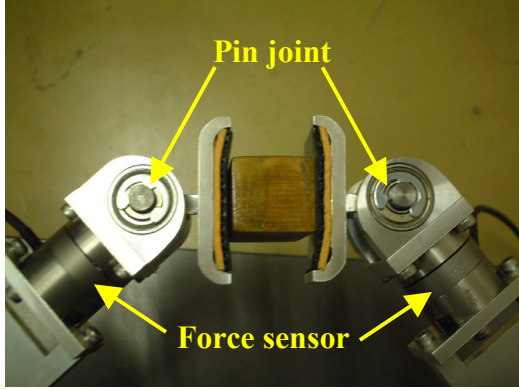


Fig. 5(b) Hand device

torque values including the effects of generated forces are calculated successively in the PC as $\tau_{I.D.}$. The main purpose of developing the system is not to create another concept of a force controller, but simply to verify the accuracy of calculated outputs, and to check the performance of the calculation itself in actual control process. The force feedback value, which is obtained by using

$$F_{feedback} = K_F(F_G - F_S), \quad (6)$$

is directly fed back into the calculation. Here, K_F is the feedback gain for force, F_G the target generating force and F_S the actual value acquired from the force sensors. The calculation is carried out incrementally in each sampling time period. The torque values on all joints are obtained after the calculation is finished for each time period. For example, it is confirmed that the calculation takes

Table 1 Feedback gain values

	J1	J2	J3	J4
K_p Nm/rad	4.5	3.5	4.5	2.5
K_D Nms/rad	1.8	1.5	1.8	1.0
K_I Nm/rad	0.04	0.06	0.02	0.04
K_F	0.00018			

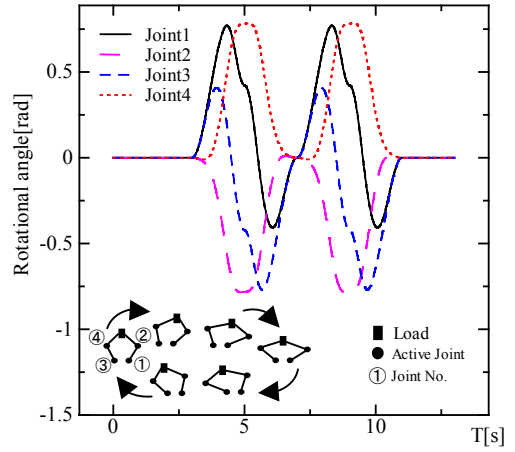


Fig. 6 Target motion for two manipulators in force control

approximately 0.7 ms by using a Celeron 1.1 GHz PC, which is short enough for practical use, when the sampling time is set to 10 ms. By adding frictional correction in motors and feedback values to $\tau_{I.D.}$, the final control torque τ is obtained as follows:

$$\tau = J\ddot{q}_d + D\dot{q}_d + f_c + \tau_{I.D.} + \tau_{feedback}, \quad (7)$$

where J is the moment of inertia of motors, D the viscosity coefficient of motors, f_c the dynamic friction force, and \dot{q}_d and \ddot{q}_d the target angular velocity and angular acceleration, respectively. $\tau_{feedback}$ is the PID feedback torque, which is obtained using

$$\tau_{feedback} = K_P(q_d - q) + K_I \int (q_d - q) + K_D(\dot{q}_d - \dot{q}), \quad (8)$$

where q and \dot{q} are the actual angle and angular velocity acquired from the attached encoders, respectively. K_P , K_I and K_D are the feedback gain for the angle, the integrated value and the angular velocity, respectively.

Figure 5 shows a set of two manipulators used in the experiment, with hand devices to hold an object. Gearless motors are adopted, in this paper, to deliberately maximize the effect of dynamics and to verify the output of the parallel solution scheme. Feedback gain values used in the experiment are shown in Table 1. The manipulators are given a task to move a woodchip (weight: 15 g) along a circle path for two times, with a constant grasping force of 0.5 N. Figure 6 shows the rotational angle for each joint and the schematic diagram of the target motion. Torque curves for each joint are obtained during the control by using the parallel solution scheme as shown in Fig. 7. The value of inverse dynamics is considerably large compared to the total torque as shown in Fig. 8, and thus, it is desirable not to disregard the calculation of inverse dynamics in this kind of motion, to maintain the stability of the control. Figures 9 and 10 show the control results of the rotational angle and the generated force. It is evident that the control results of

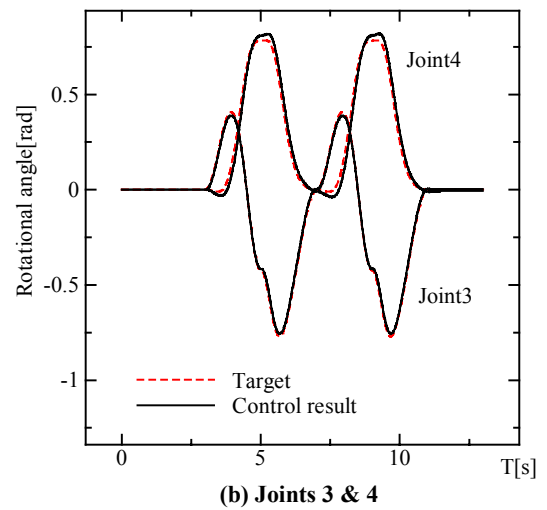
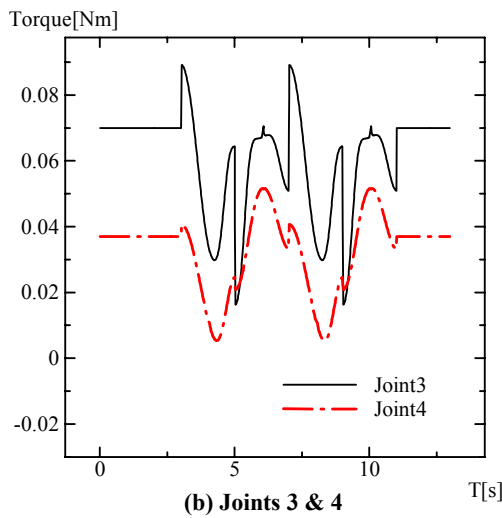
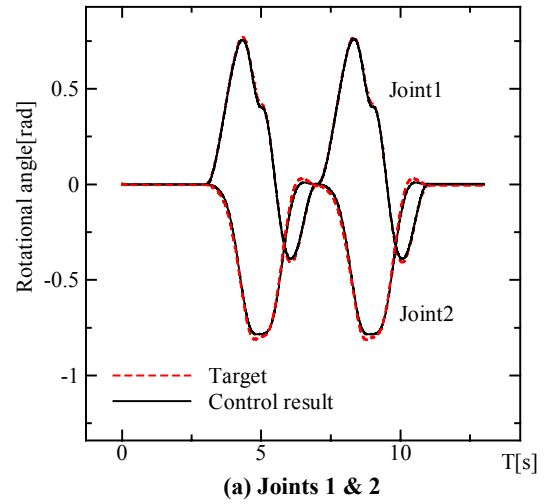
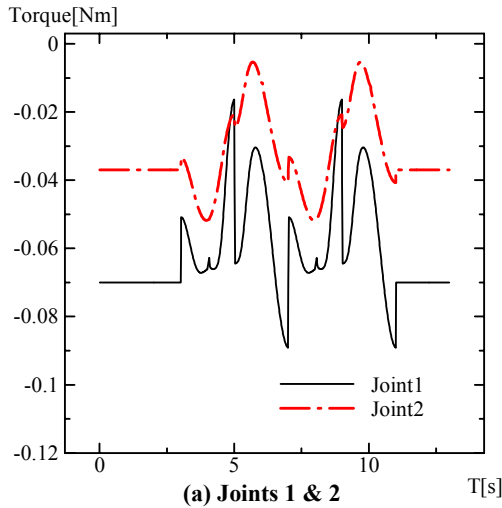


Fig. 7 Torque curves for two manipulators in force control

Fig. 9 Control results of motion

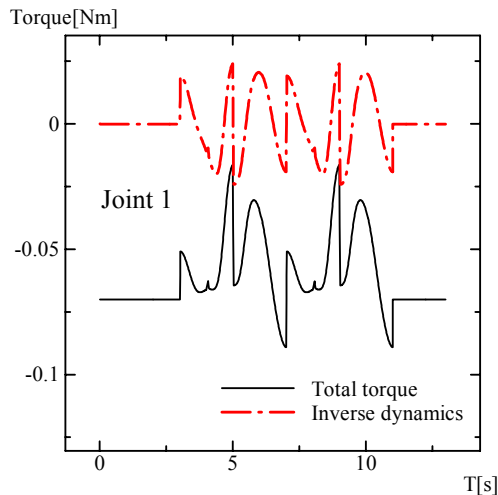


Fig. 8 Comparison of inverse dynamics against total torque

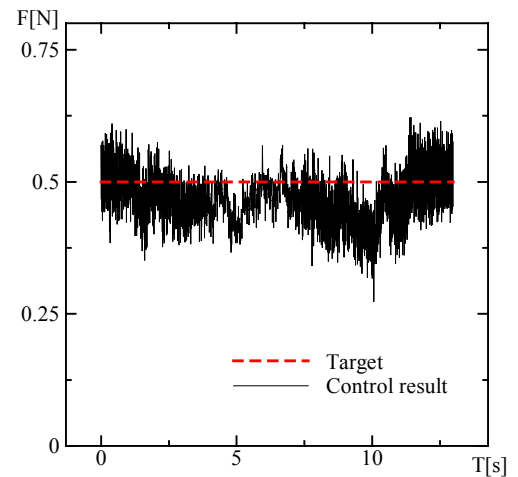


Fig. 10 Control result of generated force

motion are in good agreement with the target. Although the control result of generated force contains high-mode oscillation that is assumed to be a white noise detected by the force sensor, the generated force is consistently and

practically maintained to the target. These results confirm the validity of the torque values calculated by the parallel solution scheme.

4. Conclusion

The formerly proposed parallel solution scheme is applied to force control of link systems, where a consideration of both generated forces and dynamical effects is inevitable. The numerical and experimental results show that the accurate values of control torque considering both effects are obtained by using the parallel solution scheme. The scheme does not require derivation of Jacobian matrices and revision of dynamic equations even in such cases, and the outside frame of the numerical algorithm remains the same. The scheme can be applied to complex systems where calculations of kinematic and dynamic equations are essentially difficult.

The vector related to nodal forces, on which we focused in this paper, can contain values with both static and dynamic effects. Studies on inverse dynamics calculation and feed-forward control of flexible manipulators, which can be developed by using this feature, are in progress.

5. Acknowledgement

The authors would like to extend their appreciation for the contributions of the former members of their laboratory, Takeo Ueda, Daisaku Imaizumi, Youichi Chikugo and Atsushi Yagi.

References:

- [1] Y. Nakamura, Dynamics computation of closed link robots and optimization of actuation redundancy, *Trans. Society of Instrument and Control Engineers*, 25(5), 1989, 600–607, in Japanese.
- [2] K. Sugimoto, Deviation of equation of motion of closed loop mechanisms, *J. Robotics Society of Japan*, 15(3), 1997, 460–467, in Japanese.
- [3] Y. Nakamura and K. Yamane, Dynamics computation of structure-varying kinematic chains and its application to human figures, *IEEE Trans. Robotics and Automation* 16(2), 2000, 124-134.
- [4] D. Isobe, Y. Chikugo, D. Imaizumi, S. Sato, and A. Yagi, Feed-forward control of link mechanisms under various boundary conditions by using a parallel solution scheme, *Proc. 2003 IEEE/RSJ Int. Conf. Intelligent Robots and Systems IROS2003*, Las Vegas, 2003, 2773-2778.
- [5] D. Isobe and D. Imaizumi, A parallel solution scheme of inverse dynamics for flexible manipulators, *Proc. IASTED International Conference on Robotics and Applications (RA2003)*, Salzburg, 2003, 106-111.
- [6] N.M. Newmark, A method of computation for structural dynamics, *A.S.C.E. J. Engineering Mechanics*, 85, 1959, 67-94.