A recursive simulation algorithm for soft robotics

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Abstract

In recent years, soft robotics, which is a new research field on utilization of physical flexibility of robot systems, has been attracting attention. Active attempts have been made to develop new functions and to realize human-friendly robot systems by actively using soft materials such as rubber and resin. In order to accelerate such research on soft robotics, it is necessary to establish a high-speed and stable simulation technique for multibody systems including viscoelastic bodies such as rubber or resin as shown in Fig. 1. Therefore, in this study, we approximate the viscoelastic body with finite rigid body segments as shown in Fig. 2, and connect them with joints and linear viscoelastic elements such as Voigt model and Maxwell model to approximate the viscoelastic characteristics. The recursive dynamics calculation method[1] is used to speed up the calculation, and the generalized-α method[2] is used to stabilize the numerical integration. In particular, we propose a new method for incorporating the Maxwell model into recursive calculation and generalized-α method, and establish a simulation method suitable for soft robotics.

The multibody system including the viscoelastic body shown in Fig. 1 is modeled as shown in Fig. 2. At this time, the relationship between the generalized velocity $\boldsymbol{v}_i$ and the generalized acceleration $\boldsymbol{a}_i$ between adjacent bodies can be expressed as follows

$$\boldsymbol{v}_i = \boldsymbol{D}_i \boldsymbol{v}_{i-1} + \boldsymbol{J}_i \dot{q}_i \tag{1}$$

$$\boldsymbol{a}_i = \boldsymbol{D}_i \boldsymbol{a}_{i-1} + \boldsymbol{J}_i \ddot{q}_i + \boldsymbol{\beta}_i \tag{2}$$

where q_i is the joint variable of joint i, $\boldsymbol{D}_i$ is the transformation matrix, $\boldsymbol{J}_i$ is the Jacobian matrix, and $\boldsymbol{\beta}_i = \dot{\boldsymbol{D}}_i \boldsymbol{v}_{i-1} + \dot{\boldsymbol{J}}_i \dot{q}_i$. On the other hand, the relation of the generalized force $\boldsymbol{Q}_i^J$ transmitted through joint i and the joint driving force τ_i of joint i can be expressed as the following equation

$$\boldsymbol{Q}_i^J = \boldsymbol{M}_i \boldsymbol{a}_i + \boldsymbol{h}_i - \boldsymbol{Q}_i^O + \boldsymbol{D}_{i+1}^T \boldsymbol{Q}_{i+1}^J \tag{3}$$

$$\tau_i = \boldsymbol{J}_i^T \boldsymbol{Q}_i^J + Q_i \tag{4}$$

where $\boldsymbol{M}_i$ is the generalized mass matrix, $\boldsymbol{h}_i$ is the centrifugal and Coriolis force, and $\boldsymbol{Q}_i^0$ is the generalized force due to gravity. In addition, Q_i is the force due to the linear viscoelastic element, and in the Voigt model in which the spring and the damper are introduced in parallel, it becomes as follows.

$$Q_i(t) = k_i(q_i(t) - q_i^0) + c_i \dot{q}_i(t) \tag{5}$$

On the other hand, in the Maxwell model in which the spring and damper are introduced in series, the following equation is obtained.

$$Q_i(t) = e^{-\frac{k_i}{c_i}t} \left\{ \int_0^t e^{\frac{k_i}{c_i}\tau} k_i \dot{q}_i(\tau) d\tau - Q_i^0 \right\} \tag{6}$$

Here, k_i is the spring constant and c_i is the damper viscous damping coefficient. In the Voigt model, it is easy, but in the Maxwell model, it is not obvious how to incorporate it into the recursive dynamics calculation and the generalized-α method. In this paper, we propose a new calculation algorithm using the structure of recursive method, and formulate a fast and stable numerical simulation method for soft robotics. We carry out a numerical simulation of a manipulator in which a rubber element is included in the link and confirm the effectiveness of the proposed method (see Figures 3 and 4).

References

[1] Saha, S.K..: Dynamic modeling of serial multibody systems using decoupled natural orthogonal complement matrices. ASME J. Appl. Mech., Vol. 29, No. 2, pp. 986–996, 1999.

[2] Arnold, M.; Bruls, O.: Convergence of the generalized-α scheme for constrained mechanical systems. Multibody System Dynamics, Vol. 18, No. 2, pp. 185–202, 2007.

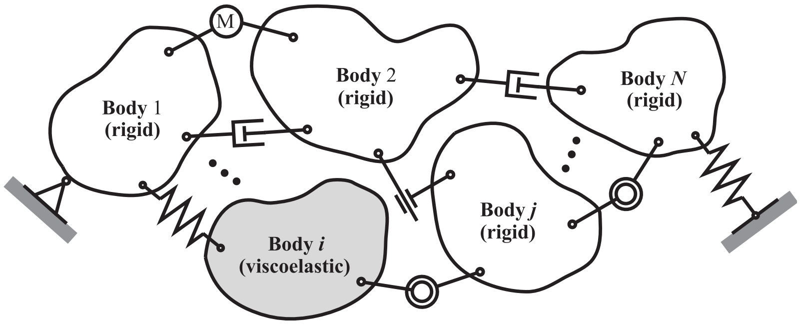

Figure 1: Multibody system with viscoelastic body

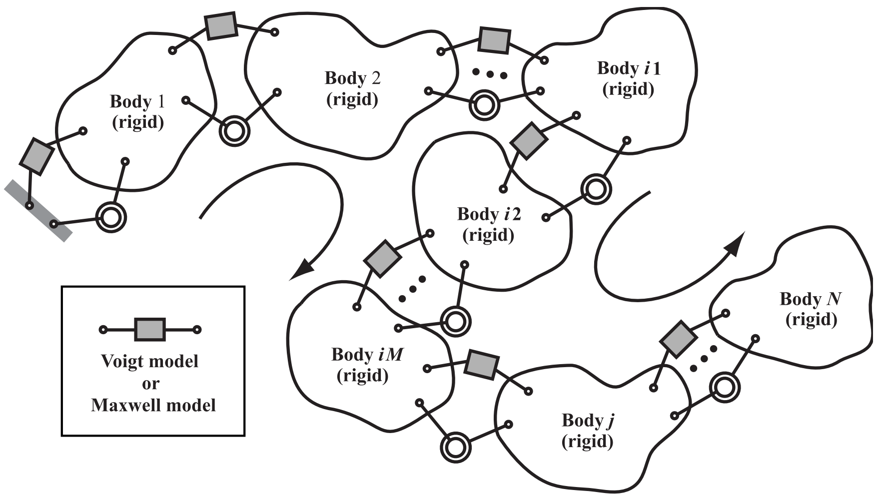

Figure 2: Finite segment approach with linear viscoelastic model

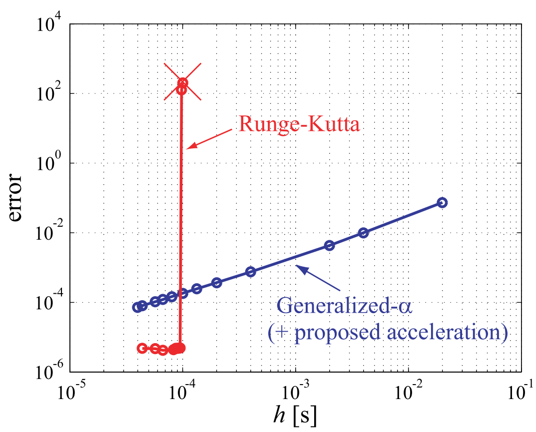

Figure 3: Comparison of integration error

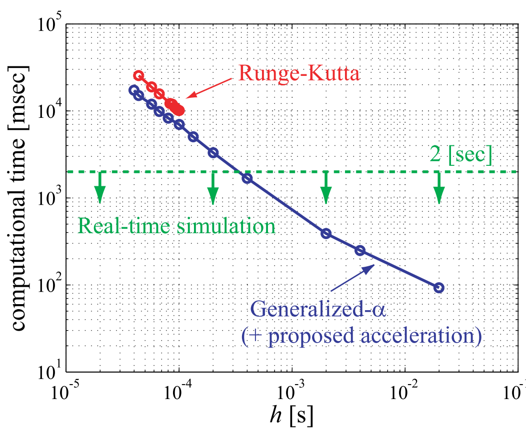

Figure 4: Comparison of computational time