Stability Guaranteed Control: Time Domain Passivity Approach

Jee-Hwan Ryu, *Member, IEEE*, Dong-Soo Kwon, *Member, IEEE*, and Blake Hannaford, *Senior Member, IEEE*

***Abstract*—A general framework for expanding the time-domain passivity control approach [12], [24] to large classes of control systems is proposed. We show that large classes of control systems can be described from a network point of view. Based on the network presentation, the large classes of control systems are analyzed in a unified framework. In this unified network model, we define "virtual input energy," which is a virtual source of energy for control, and "real output energy" that is physically transferred to a plant to allow the concept of passivity to be used to study the stability of large classes of control systems. For guaranteeing the stability condition, the time-domain passivity controller for two-port [24] is applied. Design procedure is demonstrated for a motion control system. The developed method is tested with numerical simulation in the regulation of a single link flexible manipulator. Totally stable control is achieved under wide variety of operating condition and uncertainties without any model information.**

***Index Terms*—Passivity controller, passivity observer, stability guaranteed control, time-domain passivity.**

I. Introduction

ONE of the classic problems in control theory is how to increase performance while guaranteeing stability under any operating condition and uncertainties. Toward this end, numerous advanced efforts have been undertaken. Basically two underlying philosophies have been pursued [1]: fixed control philosophy [9], [13], [14], [31], [36], and adaptive control philosophy [21], [27].

Even though these two approaches have succeeded in various of applications, the critical drawback is that these are all model-based approaches requiring the system parameters or at the very least the dynamic structure information. However, most application systems are uncertain to some degree and it is usually difficult to obtain the exact dynamic parameters and structure information.

One fruitful approach is the use of the idea of passivity to guarantee stable operation without exact knowledge of model information. The concept of passivity has traditionally been used to characterize the stability of a given system, and has been applied for designing stabilizing controllers [8]. The philosophy has its roots in classical mechanics [3], [11], and was introduced in control theory in a seminal paper by [30]. This idea has been extended to the motion control tasks of robots due to its passivity property [22]. Also, for adaptive control of robots, the passivity-based approach has been studied extensively [4], [15], [17], [27]. This has led to numerous extensions to other robot control [5], [28], [33] induction motor control [10], [19], [20], power electronics [26], and many other applications.

However, the major problem of this passivity approach for designing a stability guaranteed controller is that it is over-conservative since its closed-loop performance depends on the knowledge of model parameters, whose values are needed in order to find the added damping value. Thus, in many cases performance can be poor if a fixed damping value is used to guarantee passivity under all operating conditions [2], [18], [19]. The virtual absorber approach of [6], similarly, dissipates much more energy than the minimum required for the time domain definition of passivity.

Recently, a totally different passivity based approach has been proposed by Hannaford and Ryu [12] that injects variable damping without any knowledge of model information to reduce conservatism. They proposed a passivity observer (PO) and a passivity controller (PC) to insure stable contact under a wide variety of operating conditions. This approach has been successfully implemented to haptic interfaces [12] and teleoperation systems [24].

In this paper, we extend the time-domain passivity approach for large classes of control systems. A general framework for applying the PO/PC to large classes of control systems is proposed, and the detailed design procedure is introduced with motion control systems. The proposed idea is tested with single-link flexible manipulator simulation.

II. Review of the Time Domain Passivity Control

A. One-Port Network

In this section, we briefly review time-domain passivity control. First, we define the sign convention for all forces and velocities so that their product is positive when power enters the system port (Fig. 1). Also, the system is assumed to have initial stored energy $E(0) = 0$ at $t = 0$. The following widely known definition of passivity is used.

Definition 1: The one-port network, N, with initial energy storage $E(0)$ is passive if and only if

$$\int_0^t f(\tau)\dot{x}(\tau)d\tau + E(0) \geq 0, \quad \forall t \geq 0 \tag{1}$$

Manuscript received March 26, 2003. Manuscript received in final form February 11, 2004. Recommended by Associate Editor A. Kelkar. This work was supported by a Grant from Ford Motor Company, and the Postdoctoral Fellowship Program of the Korea Science and Engineering Foundation (KOSEF).

J.-H. Ryu is with the Department of Electrical Engineering and Computer Science, Korea Advanced Institute of Science and Technology, Taejeon, 305-701, Korea (e-mail: jhryu@rit.kaist.ac.kr).

D.-S. Kwon is with the Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Taejeon, 305-701, Korea (e-mail: kwonds@kaist.ac.kr).

B. Hannaford is with the Department of Electrical Engineering, University of Washington, Seattle, WA 98195 USA (e-mail: blake@u.washington.edu).

Digital Object Identifier 10.1109/TCST.2004.833648

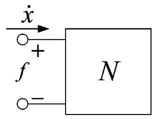


Fig. 1. One-port network.

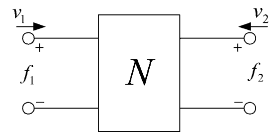


Fig. 2. Two-port network.

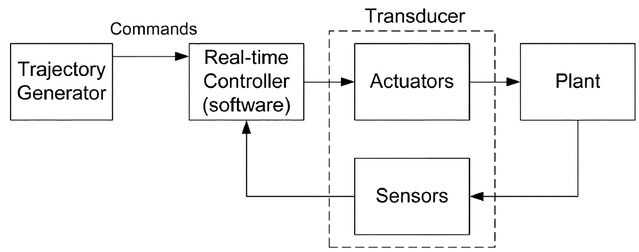


Fig. 3. Traditional view of large classes of control systems.

for forces (f) and velocities ($\dot{x}$). Equation (1) states that the energy supplied to a passive network must be greater than negative $E(0)$ for all time [32], [34].

The conjugate variables that define power flow in such a system are discrete-time values, and the analysis is confined to systems having a sampling rate substantially faster than the dynamics of the system. We assumed that there is no change in force and velocity during one sample time. Thus, we can easily "instrument" one or more blocks in the system with the following PO for a one-port network to check the passivity (1):

$$E_{\text{obsv}}(k) = \Delta T \sum_{j=0}^{k} f(t_j)v(t_j) + E(t_0) \tag{2}$$

where ΔT is the sampling period. If $E_{\text{obsv}}(k) \geq 0$ for every k, this means the system dissipates energy. If there is an instance when $E_{\text{obsv}}(k) < 0$, this means the system generates energy and the amount of generated energy is $-E_{\text{obsv}}(k)$. Recently, other research has allowed this constant force and velocity assumption to be relaxed [25], [29],

Consider a one-port system which may be active. Depending on operating conditions and the specifics of the one-port element's dynamics, the PO may or may not be negative at a particular time. However, if it is negative at any time, we know that the one-port may then be contributing to instability. Moreover, we know the exact amount of energy generated and we can design a time-varying element to dissipate only the required amount of energy. We call this element a PC. The PC takes the form of a dissipative element in a series or parallel configuration depending on the input causality [12].

B. Two-Port Network

Similar to the one-port case, the PO can be designed for a two-port network (Fig. 2)

$$E_{\text{obsv}}(k) = \Delta T \sum_{j=0}^{k} (f_1(t_j)v_1(t_j) + f_2(t_j)v_2(t_j)) + E(t_0). \tag{3}$$

However, unlike in the one-port case, there are two gateways through which the generated energy flows out. Theoretically, the two-port network can be made passive by placing the PC at either port. However, there might be some instance where the two-port network generates energy ($E_{\text{obsv}}(k) < 0$), even though the input signal (velocity for impedance causality and force for admittance causality) of a port where the PC is placed is zero. Consequently, another PC should be placed at the other port.

In addition, we have to consider how to activate the PC at each port to make the two-port passive. Mathematically, there are two ways to make the two-port network passive (the total sum of energy is greater than zero). The first way is to make the produced energy less than the absorbed energy. The other way is to make the absorbed energy greater than the produced energy. However, it is more feasible way to make the produced energy less than the absorbed energy by monitoring the conjugate signal pair ($f_1 v_1$ and $f_2 v_2$) of each port in real time, when the two-port network becomes active.

Please see [12], [24], and [25] for more detail about time-domain passivity control approach.

III. Network Representation

Since the PO/PC approach was based on energy monitoring method, it is required to express a large classes of control systems in network point of view with energy flows for PO/PC application. In this section, we introduce the method to express the large classes of control systems in network model with energy flows.

From a traditional control point of view, a large class of control systems may be represented as in Fig. 3 and are composed of a trajectory generator, a real-time controller (software), a transducer (sensors and actuators), and a plant. The high-level trajectory generator plans movement tasks, and gives a command to the low-level real-time controller, which consists of a control law. The controller operates the plant, which is composed of a system hardware structure and an environment through the transducer that is composed of sensors and actuators.

The traditional control system view(Fig. 3) can be analyzed in terms of energy flow by representing it in a network point of view. Energy here is defined as the integral of the inner product between the conjugate input and output, which may or may not correspond to a physical energy. First, we partition the block diagram into three elements, the trajectory generator (consisting of the trajectory generator), the control element (consisting of the controller, actuator, and sensors) and the plant (consisting of the plant). The connection between the controller element and the plant is a physical interface at which, suitable conjugate variables define the physical energy flow between controller and plant. The connection between trajectory generator and controller, which traditionally consists of a one-way command information flow, is modified by the addition of a virtual feedback of the conjugate variable. For a motion control system, the trajectory generator output would be a desired velocity (v_d) , and

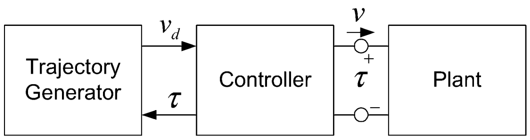


Fig. 4. Network view of a motion control system.

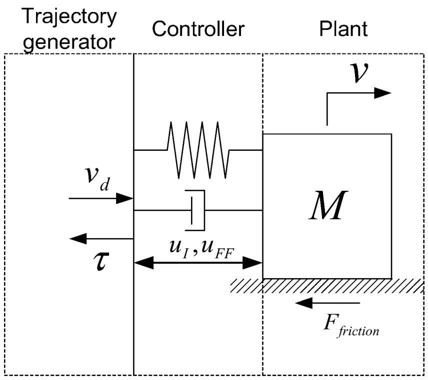


Fig. 5. Physical analogy of a motion control system.

the virtual feedback would be equal to the controller output (τ) (Fig. 4).

A. Motion Control Systems

To show that the above consideration is generally possible for motion control systems, we physically interpret these energy flows. We consider a general tracking control system with a position PID and feedforward controller for moving a mass (M) on the floor with a desired velocity (v_d). The control system can be described by a physical analogy with Fig. 5. The position PD controller is physically equivalent to a virtual spring and damper whose reference position is moving with a desired velocity. In addition, integral controller (u_I) and the feedforward controller (u_{FF}) can be regarded as internal force sources. Since the mass and the reference position are connected with the virtual spring and damper, we can obtain the desired motion of the mass by moving the reference position with the desired velocity. The important point is that if we want to move the reference position with the desired velocity, force is required. This force is determined by the impedance of the controller and the plant. Physically this force is equivalent to the controller (PID and feedforward) output (τ). As a result, the conjugate pair (v_d and τ) simulates the flow of virtual input energy from the trajectory generator, and the conjugate pair (v and τ) simulates the flow of real output energy to the plant. Through the above physical interpretation, we can construct a network model for general tracking control systems (Fig. 4), and this network model is equivalently described with Fig. 6 whose trajectory generator is a current (or velocity) source with electrical–mechanical analogy. Note that electrical–mechanical analog networks enforce equivalent relationships between effort and flow. For the mechanical systems, forces replace voltages in representing effort, while velocities representing currents in representing flow.

B. Generalization

For other kinds of control systems, if each trajectory generator can equivalently be described as an electric circuit with a

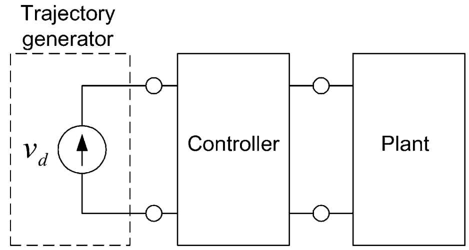


Fig. 6. Equivalent network view of a motion control system for circuit analysis.

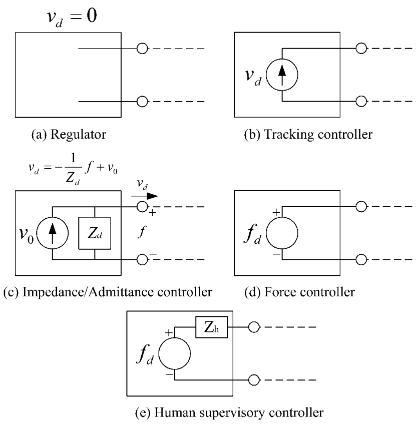


Fig. 7. Network model of trajectory generators.

port (like Fig. 6) by adding feedback of the conjugate variable to the trajectory generator, we can contruct a network model. To show the generality of the network expression, we represent the trajectory generator of five types of controllers as electric circuits with a conjugate pair. Fig. 7(a) shows the trajectory generator of a regulator. The trajectory generator can be represented as an open circuit that gives zero velocity ($v_d = 0$). For a tracking controller, as mentioned already in Fig. 6, the trajectory generator is equivalent to a current (or velocity) source [Fig. 7(b)]. The trajectory generator of an impedance/admittance controller can be represented as a circuit with a current (or velocity) source and a parallel impedance element [Fig. 7(c)]. The desired velocity is modified to have desired impedance/admittance by the parallel impedance model. The trajectory generator of a force controller is equivalent to a voltage (or force) source [Fig. 7(d)]. For the case of human supervisory control where the human is involved in the control loop (such as haptic and teleoperation), the trajectory generator is dependent on the human and this system can be regarded as a circuit with a voltage (or force) source and series impedance that indicates the biomechanics of the human [Fig. 7(e)]. Note that the feedback conjugate variable from the controller does not imply that the trajectory generator actually uses the information. Of the five forms of control shown above, only impedance/admittance and human supervisory control modify the conjugate variable (command) in response to feedback. In all cases, however, we can construct a conjugate pair to express the flow of virtual energy, and use it as a bookkeeping device to keep track of it.

Considering the controller element of Fig. 7, we can define two important quantities, the "virtual input energy" and the "real output energy" of the controller. This can be made possible by

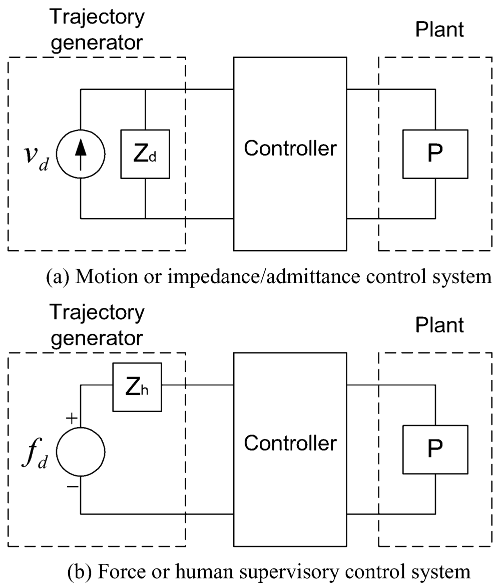


Fig. 8. Equivalent two electric network circuits with large classes of control systems.

adding a virtual port at input side of the controller. The "virtual input energy" is defined as the integral of the inner product between the trajectory generator output and its conjugate variable (v_d and τ for motion control systems), which is fed back from the controller. This virtual input energy is generated to give a command to the controller, and the controller transmits the input energy to the plant through the transducer in the form of real physical energy. We define the energy that is physically transferred to the plant as the "real output energy."

The important result in defining the "virtual input energy" is to move the source of energy from the controller to the trajectory generator. Thus, it becomes possible to represent the controller as a two-port, which characterizes the exchange of energy between the trajectory generator and the plant. As a result, this definition allows useful tools in network theory such as passivity to be used to study stability. The following section addresses this in detail.

IV. Stability Condition

Based on the network model in the above Section, large classes of control systems can be represented as two electric network circuits with either current source or effort source (Fig. 8). The current source trajectory generator represents the traditional motion control system ($Z_d = \infty$) or impedance/admittance control system ($Z_d \neq \infty$). The effort source represents the command to a force control system ($Z_h = 0$) or the human supervisory control system ($Z_h \neq 0$).

From the circuit representation (Fig. 8), we find that the virtual input energy from the trajectory generator depends on the impedance of the connected network. If the connected network (controller and plant) with the trajectory generator is passive, the control system can remain passive [8] since the trajectory generator creates just the amount of energy necessary to make up for the energy losses of the connected passive network. This is just like a normal electric circuit. Thus, we have to make the connected network passive to guarantee the stability of the control system since passivity is a sufficient condition for stability.

In addition, the plant is uncertain and has a wide variation range of impedance or admittance (from zero to infinite). Thus, the controller two-port should be passive to guarantee stability with any passive plant. At this point, the two-port approach, which has been introduced in [24] to ensure stable teleoperation, can be applied to make the controller two-port passive.

We can also draw the same conclusion based on the method that has been used in the teleoperation area [2], [35]. If we assume that the trajectory generator and the plant are passive, the controller itself must be passive to meet the sufficient condition for passivity. Strictly speaking, however, the trajectory generator is not passive because it has a force/velocity source as the power source. Colgate and Hogan [7] noted that even if the system has an active term, system stability is guaranteed unless the active term is in some way state dependent. Obviously, the trajectory generator is passive when $v_d = 0$ or $f_d = 0$. Therefore, we can make the following assumption, "the trajectory generator input v_d or f_d is independent of the state of the controller and plant. In other words, the trajectory generator does not generate v_d or f_d that will cause the system to be unstable." The above assumption seems tricky in a sense, but it is necessary to ensure system stability by passivity.

V. Problem Formulation for Motion Control Systems

In this section, we present the detailed design procedure of the PO/PC approach for a motion control system. First, for designing the PO, it is necessary to check the real-time availability of the conjugate variables at each port of the controller (Fig. 4). The conjugate variables at the controller output port are usually available since the output velocity (v) is measured and the controller output (τ) is same as the real-time calculated output (τ_c). Furthermore, the conjugate variables are generally available for the controller input port since the desired velocity (v_d) is given, and the same controller output (τ_c) is used. In addition to the real-time availability, the conjugate output (which depends on causality) should be changed to a desired value in real-time for implementing the PC. For the motion control systems (Fig. 4), we can modify the conjugate output (τ) at the controller output port in real-time by modifying the calculated output (τ_c). Thus, the PO is designed as

$$E_{\text{obsv}}(k) = \Delta T \sum_{j=0}^{k} (\tau_c(t_j) v_d(t_j) - \tau_c(t_j) v(t_j)) + E(0). \quad (4)$$

However, there might be some cases in which these conjugate variables are not available or modifiable. In such cases, we can use extra sensors for measuring the conjugate variables or exclude passive subsystems until constructing an accessible pair of conjugate variables without ruining the overall passivity [24].

After designing the PO, the causality of each port of the controller should be determined in order to choose the type of PC for implementation. In a motion control system, the output of the trajectory generator is the desired velocity (v_d) of the point

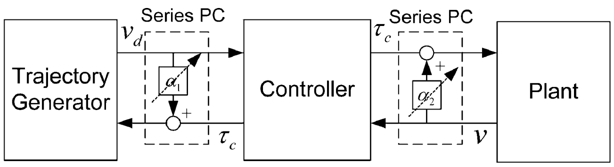


Fig. 9. Configuraton of PC for a motion control systems.

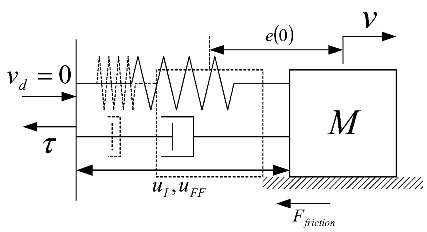


Fig. 10. Physical analogy of a motion control system with initial position error (dashed figure is a equilibrium posture).

of interest, and the controller output (τ_c) is feedback to the trajectory generator. Thus, the port that is connected with the trajectory generator has impedance causality. Also, the other port of the real-time controller usually has impedance causality because many motion controlled physical plants have admittance causality [force input (τ_c) and velocity output (v)]. Thus, two series PCs have to be placed at each port to guarantee the passivity of the controller (Fig. 9).

In Section II, the initial stored energy of the network was used for designing the PC. It is necessary to clarify the value of the initial energy storage of the controller. From Fig. 5, assuming that the spring is initially deformed $e(0)$ from the equilibrium position, the motion control system can then be described by a physical analogy with Fig. 10. For a regulation problem, the error between the equilibrium position and the initial position of the plant can be considered as the initial position error of the controller. From a physical point of view, in this configuration, the only energy storage element in the controller is the "spring." The damper is dissipating energy, and the integral and feedforward controller is neither an energy storage nor a dissipation element but only an effort source. Thus, only the position P controller has initial energy storage at the starting time given by the following:

$$E(0) = \frac{1}{2}K_p e(0)^2 \tag{5}$$

where K_p is a proportional gain and $e(0)$ is the position error at the starting time.

For a SISO control system, it is straightforward to construct conjugate pairs for simulating virtual input and real output energy. However, for a case where there are multiple outputs that we use for generating one control input, such as in a SIMO or MIMO control system, it is important to know which velocity output is used for simulating energy output to the plant. In this case, the velocity output (v) should be the velocity at the actuating position due to the important physical fact that the physical energy only flows into the plant through the place where the actuator is placed. Thus, if it is possible, and it generally is, to use the velocity information of the actuating position, we can always calculate the physical energy flow into the plant.

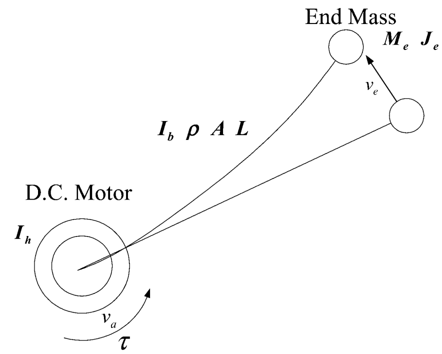


Fig. 11. Single link flexible manipulator.

VI. Numerical Simulations

Many researchers have used a flexible manipulator for testing newly developed control methods due to its significant control challenges. In this section, the proposed stability guaranteed control scheme is tested for feasibility with a simulated flexible link manipulator.

The experimentally verified single link flexible manipulator model [16] is employed in this paper. A single link flexible manipulator having a planar motion is detailed in Fig. 11. The rotational inertia of the servo motor, the tachometer, and the clamping hub are modeled as a single hub inertia I_h. The payload is modeled as an end mass M_e and a rotational inertia J_e. The joint friction is included in the damping matrix. The system parameters in Fig. 11 are given in Table I. The closed-form dynamic equation is derived using the assumed mode method. For the system dynamic model, the flexible mode is modeled up to the third mode, that is, an eighth-order system is considered.

A. Regulation Problem With a Large Payload Variation and Parameter Uncertainties

In this simulation, we applied the proposed approach to guarantee the stability for the regulation of a flexible manipulator that has model uncertainties and large payload variations. The control task is to regulate the tip position from the zero initial state to the desired point (0.1 m) with a nominal LQ regulator that has been designed with the following weighting matrices, $Q = diag[25\ 0\ 0\ 0\ 0\ 0\ 0.1\ 0\ 0]$, $R = 0.1$.

In the first simulation, the regulation problem is simulated to challenge the robustness of the designed LQ regulator. The tip mass and tip rotational inertia were perturbed by -70%, and the damping and stiffness matrices of the link were perturbed by $+50\%$ and -30% from the nominal values, respectively. The virtual input energy is zero (since this is a regulating problem), and the hub angular velocity is used (see Section V) for calculating the real output energy by making the conjugate pair with joint torque. Using (5), the initial energy storage ($E(0) = 0.055$) is calculated. With the perturbed parameters, control is unstable, tip position and control input have oscillation which increases with time [Fig. 12(a) and (b)]; the PO [Fig. 12(c)] was initially greater than the negative value of the initial stored energy, but grew to increasingly more negative values.

In the second simulation, with the PC turned on, the same regulation problem as Fig. 12 is simulated. Even though the con-

TABLE I
PHYSICAL PROPERTIES OF A SINGLE-LINK FLEXIBLE MANIPULATOR

Link	Tip mass	Hub
Stiffness (EI): $11.85Nm^2$ Thickness (H): $47.63e-4m$ Unit length mass (ρA): $0.2457Kg/m$ Length (L): $1.1938m$	Mass (M_e): $0.5867Kg$ Rotational inertia (J_h): $0.2787Kgm^2$	Rotational inertia (I_h): $0.016Kgm^2$

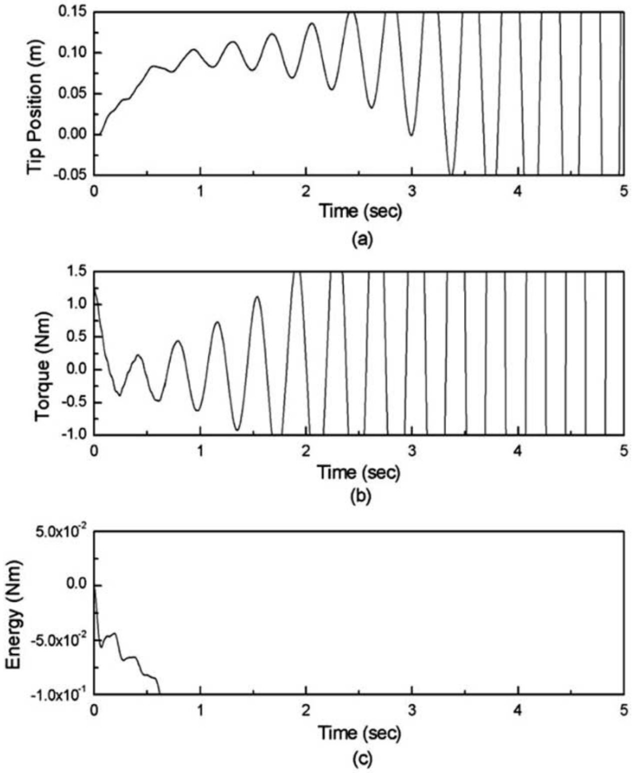


Fig. 12. Regulation without the PC and with perturbation.

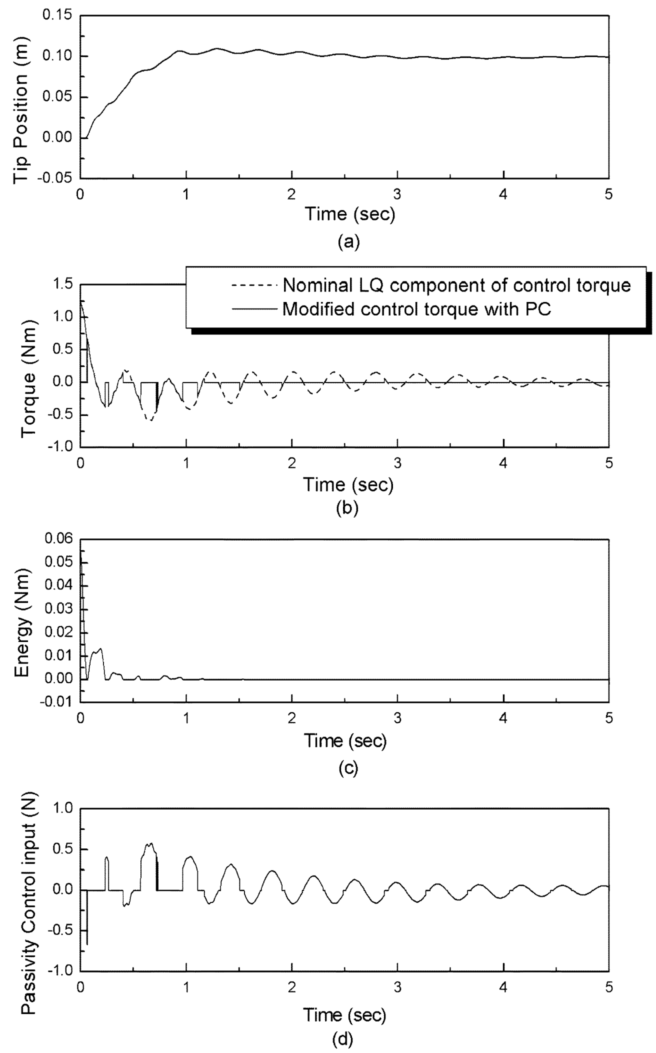


Fig. 13. Regulation with the PC and perturbation.

troller is highly active, the PC can make the transmitted energy remain below the initial stored energy [Fig. 13(c)]. The oscillation is removed and tip position converges to the desired value [Fig. 13(a)]. During the rise time, the PC is activated only for several short periods when the PC input is required [Fig. 13(d)]. That means the PC input modifies the nominal LQ regulator as minimally as possible [Fig. 13(b)].

B. Comparison With Conventional Robust Controllers

In the next simulation, we compare the proposed approach with the conventional robust control approach for showing the lesser conservativeness of the proposed approach. In conventional robust controller design methods, since these controllers are designed with consideration of the overall uncertainty variation, the resulting controller gains are very high. Thus, the control performance used to be poor and in some cases these controller gains cannot be applied in practice due to the actuator limits and noise magnifying problems.

Since we use a nominal LQ regulator in the above section, we use a conventional robust LQ regulator that uses structure information of the uncertainties and a polytopic robust LQ regulator [23] that has been considered less conservative than the conventional robust LQ regulator for comparison. For the same system with the above simulation, the conventional robust LQ regulator can guarantee $\pm 40\%$, and the polytopic robust LQ regulator guarantees $\pm 80\%$ inertia perturbation from the nominal value in the presence of $\pm 50\%$ stiffness and $\pm 30\%$ damping perturbation [23]. However, these robust controllers show very poor control performance. Fig. 14 shows the control result of the polytopic LQ regulator (designed for $\pm 70\%$ inertia perturbation) with the same conditions as those in Fig. 13. The response is very slow [Fig. 14(a)], and the controller requires up

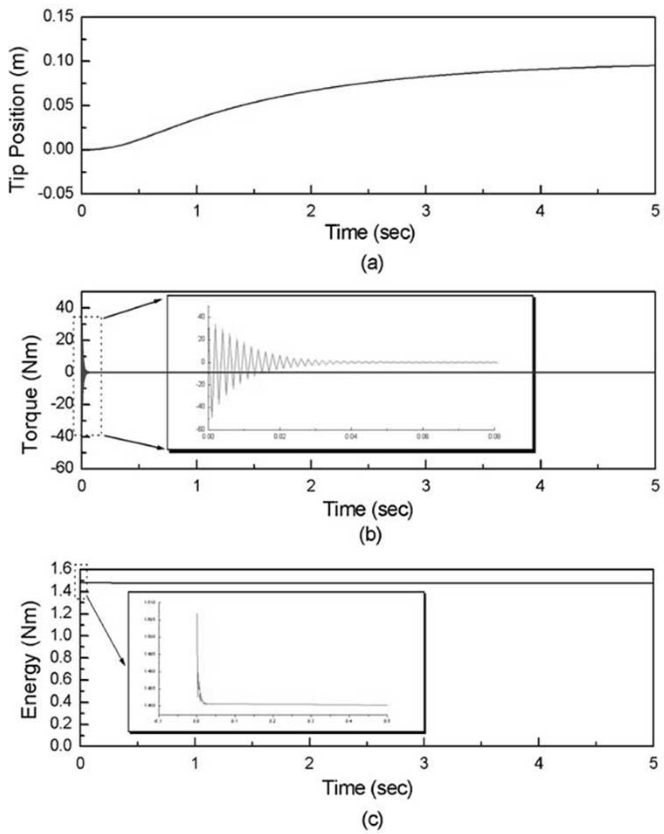


Fig. 14. Conventional robust control (polytopic robust LQ regulator).

to 50 Nm of control input compared with only 1.5 Nm in the proposed approach.

On the other hand, the PO/PC approach minimally degrades the performance even though this extends the allowable amount of perturbation significantly. Theoretically, there is no limitation if the perturbation is physically allowable (for example, mass cannot be negative). We compare the performance of our approach with the nominal LQ control (Fig. 15). When there are no parameter perturbations, the control with the nominal LQ and the PC is same as the nominal LQ without the PC. When there are parameter perturbations (same amount with Fig. 13), the control performance with PC was similar. Notice that the nominal LQ regulator shows the best performance when there are no parameter perturbations. The important point in our approach is that the PC is only activated when it is required and during the other periods the control is equivalent to the nominal LQ regulator [Fig. 15(b)].

C. Velocity Noise Problem

The need for velocity information shows one drawback of this approach. Although control systems are generally equipped with high-precision sensors for position measurement, velocity measurements are often contaminated with a considerable amount of noise due to quantization effect. The same regulation problem as Fig. 13 was simulated considering velocity noise from quantization at 2×10^{-5} (rad). In this case, the passivity control input [Fig. 16(d)] had a similar envelope with the passivity control input of Fig. 13(d), followed by a noise-like signal during a period of low velocity [Fig. 16(c)]. Thus, the performance was slightly degraded [Fig. 16(a) and (b)], although stable regulation was achieved.

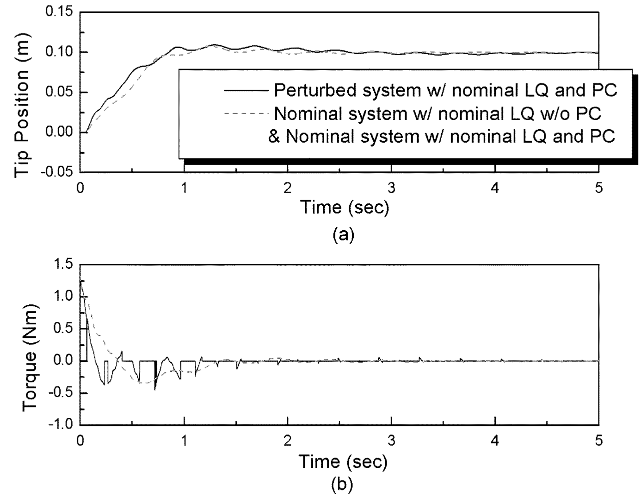


Fig. 15. Comparison of the performance of the PC approach with the nominal LQ control with and without perturbation. Case of nominal LQ control with perturbation is unstable (not plotted).

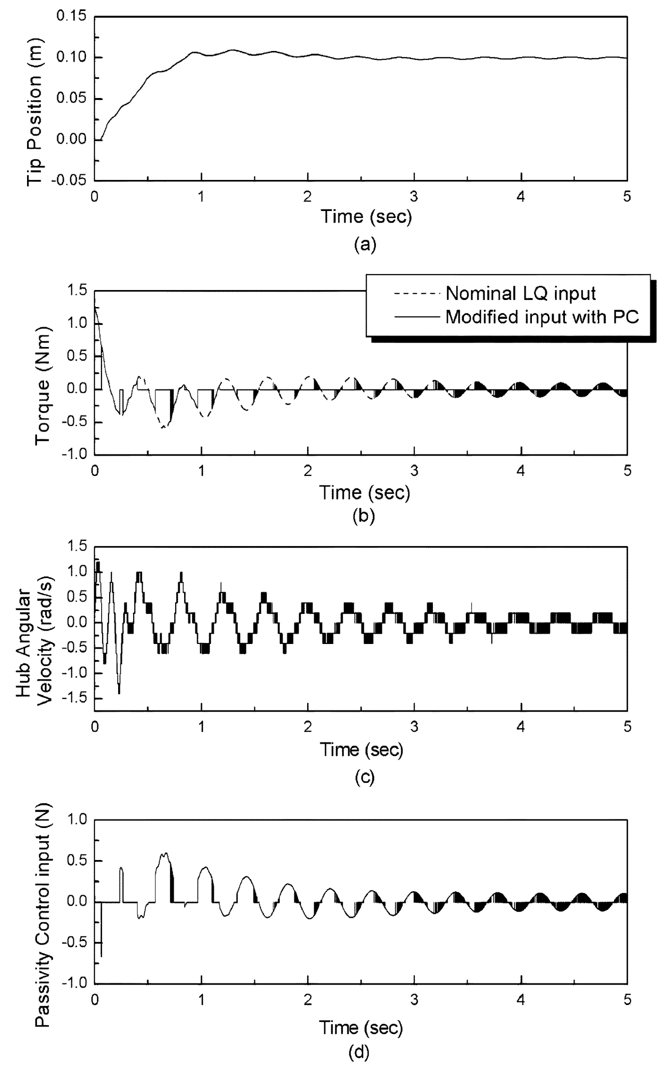


Fig. 16. Regulation with the PC when quantization effect is added.

VII. Conclusion and Futher Works

The time-domain passivity approach is expanded for large classes of control systems. The major contribution of the proposed approach is that the general framework of the time-domain passivity approach for large classes of control systems is proposed. Numerical simulations have validated the efficiency of the theoretical methods. The proposed PO/PC approach shows significantly increased performance compared to conventional robust controller while guaranteeing stability. Totally stable control for large classes of control systems are expected.

Due to the generality and simplicity of the algorithm, the PO and PC can both be implemented for guaranteeing stability with simple software modifications in any kind of existing conventional control scheme.

As a further work, we intend to study ways of removing the noise behavior of the PC during low values of velocity.

References

[1] C. Abdallah, D. Dawson, P. Dorato, and M. Jamshidi, "Survey of robust control for rigid robots," *IEEE Control Systems Magazine*, vol. 11, pp. 24–30, Jan. 1991.

[2] R. J. Anderson, "A network approach to force control in robotics and teleoperation," Ph.D. dissertation, Dept. Elect. Comput. Eng., Univ. Illinois, , Urbana-Champaign, IL, 1989.

[3] V. I. Arnold, *Mathematical Methods of Classical Mechanics*, 2nd ed. New York: Springer-Verlag, 1989.

[4] D. S. Bayward and J. T. Wen, "Simple robust control laws for robotic manipulators, part II: Adaptive case," in *Proc. JPL/NASA Telerobotics Workshop*, Jan. 1987.

[5] H. Berghuis and H. Nijmeijer, "A passivity approach to controller-observer design for robots," *IEEE Trans. Robot. Automat.*, vol. 9, pp. 740–754, Dec. 1993.

[6] R. T. Bupp, D. S. Bernstein, V. S. Chellaboina, and W. M. Haddad, "Resetting virtual absorbers for vibration control," *J. Vibrat. Control*, vol. 6, pp. 61–83, 2000.

[7] J. E. Colgate and N. Hogan, "Robust control of dynamically interacting systems," *Int. J. Control*, vol. 48, no. 1, pp. 65–88, 1988.

[8] C. A. Desoer and M. Vidyasagar, *Feedback Systems: Input-Output Properties*. New York: Academic, 1975.

[9] J. C. Doyle, "Robustness of multiloop linear feedback systems," in *Proc. IEEE Int. Conf. Decision and Control*, 1979, pp. 12–18.

[10] G. Espinosa-Perez, P. J. Nicklasson, and R. Ortega, "State observers are unnecessary for induction motor control," *Syst. Control Lett.*, vol. 23, no. 5, pp. 315–323, 1994.

[11] H. Goldstein, *Classical Mechanics*, 2nd ed. Reading, MA: Addison-Wesley, 1980.

[12] B. Hannaford and J. H. Ryu, "Time domain passivity control of haptic interfaces," *IEEE Trans. Robot. Automat.*, vol. 18, pp. 1–10, Feb. 2002.

[13] U. Itkis, *Control Systems of Variable Structure*. Jerusalem, Israel: Keter, 1976.

[14] H. Kwakernaak, "Robust control and -optimization – Tutorial paper," *Automatica*, vol. 29, no. 2, pp. 255–273, 1993.

[15] R. Kelly, R. Carelli, and R. Ortega, "Adaptive motion control design of robot manipulators: An input-output approach," *Int. J. Control*, vol. 50, pp. 2563–2581, 1989.

[16] D. S. Kwon and W. J. Book, "Time-domain inverse dynamic tracking control of a single-link flexible manipulator," *J. Dynam. Syst., Meas. Control*, vol. 116, no. 2, pp. 193–200, 1994.

[17] I. D. Landau and R. Horowitz, "Applications of the passive systems approach to the stability analysis of adaptive controllers for robot manipulators," *Int. J. Adapt. Control Signal Process.*, vol. 3, pp. 23–38, 1989.

[18] C. A. Lawn and B. Hannaford, "Performance testing of passive communication and control in teleoperation with time-delay," in *Proc. IEEE Int. Conf. Robotics Automation*, Atlanta, GA, May 1993, pp. 776–781.

[19] P. J. Nicklasson, R. Ortega, and G. Espinosa-Perez, "Passivity-based control of a class of blondel-park transformable electric machines," *IEEE Trans. Automat. Contr.*, vol. 42, pp. 629–647, May 1997.

[20] R. Ortega, P. J. Nicklasson, and G. Espinosa-Perez, "On speed control of induction motors," *Automatica*, vol. 32, no. 3, pp. 455–460, 1996.

[21] R. Ortega and M. W. Spong, "Adaptive motion control of rigid robots: A tutorial," in *Proc. IEEE Conf. Decision and Control*, Austin, TX, 1988, pp. 1575–1584.

[22] B. Paden and R. Panja, "Globally asymptotically stable 'PD+' controller for robot manipulators," *Int. J. Control*, vol. 47, pp. 1697–1712, 1988.

[23] J. H. Ryu, D. S. Kwon, and Y. Park, "A robust controller design method for a flexible manipulator with a large time varying payload and parameter uncertainties," *J. Intell. Robot. Syst.*, vol. 27, pp. 345–361, 2000.

[24] J. H. Ryu, D. S. Kwon, and B. Hannaford, "Stable teleoperation with time domain passivity control," *IEEE Trans. Robot. Automat.*, vol. 20, pp. 365–373, Apr. 2004.

[25] J. H. Ryu, Y. S. Kim, and B. Hannaford, "Sampled and continuous time passivity and stability of virtual environments," in *IEEE Trans. Robot. Automat.*, vol. 20, Aug. 2004, pp. 772–776.

[26] H. Sira-Ramirez, R. Ortega, R. Perez, and M. Garcia, "Passivity-based controllers for the stabilization of DC-to-DC power converters," in *Proc. 34th IEEE Conf. Decision Control*, New Orleans, LA, 1995, pp. 3471–3476.

[27] J. J.-E. Slotine and W. Li, "On the adaptive control of robot manipulators," *Int. J. Robot. Res.*, vol. 6, pp. 49–59, 1987.

[28] S. Stramigioli, *Modeling and IPC Control of Interactive Mechanical Systems: A Coordinate Free Approach*. New York: Springer-Verlag, 2001.

[29] S. Stramigioli, C. Secchi, and A. J. van der Schaft, "A novel theory for sampled data system passivity," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robotics and Systems*, Switzerland, 2002, pp. 1936–1941.

[30] M. Takegaki and S. Arimoto, "A new feedback method for dynamic control of manipulators," *ASME J. Dynam. Syst. Meas. Contr.*, vol. 102, pp. 119–125, 1981.

[31] V. I. Utkin, *Sliding Modes and Their Application in Variable Structure Systems*. Moscow: Mir, 1978.

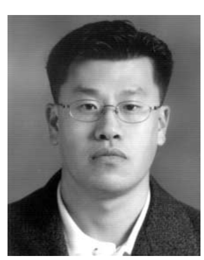
[32] A. J. van der Schaft, *L2-Gain and Passivity Techniques in Nonlinear Control*. New York: Springer-Verlag, 2000, Communications and Control Engineering Series.

[33] J. T. Wen, "Robot control by using the concept of passivity," *IEEE Control Syst. Mag.*, pp. 62–73, Jan. 1991.

[34] J. C. Willems, "Dissipative dynamical systems, Part I: General theory," *Arch. Ration. Mech. Anal.*, vol. 45, pp. 321–351, 1972.

[35] Y. Yokokohji and T. Yoshikawa, "Bilateral control of master-slave manipulators for ideal kinesthetic coupling-formulation and experiment," *IEEE Trans. Robot. Automat.*, vol. 10, pp. 605–620, Oct. 1994.

[36] G. Zames, "Feedback and optimal sensitivity: Model reference transformations, weighted seminars, and approximation inverses," in *Proc. Allerton Conf.*, 1979, pp. 744–752.



Jee-Hwan Ryu (M'02) received the B.S. degree in mechanical engineering from Inha University, Inchon, Korea, in 1995, and the M.S. and Ph.D. degrees in mechanical engineering from Korea Advanced Institute of Science and Technology (KAIST), Taejon, Korea, in 1995 and 2002, respectively.

Before graduate study, in 1998, he worked as a Visiting Graduate Student in the Biorobotics Division, Mechanical Engineering Laboratory, Tsukuba, Japan, and as a Visiting Scholar in the Biorobotics Laboratory, Department of Electrical Engineering, University of Washington, Seattle, from April to July 2000. At KAIST, he pursued thesis research in stable control of teleoperator and haptic interfaces. From March 2002 to April 2003, he worked in the Department of Electrical Engineering, University of Washington, as a Research Assistant. Since May 2003, he has been at KAIST, where he has been a Research Assistant Professor of Information and Electronics Research Institute. His current active research interests include haptic displays and intelligent robotics.

Dong-Soo Kwon (S'89–M'97) received the B.S. degree in mechanical engineering from Seoul National University, Seoul, Korea in 1980, the M.S. degree in mechanical engineering from Korea Advanced Institute of Science and Technology (KAIST), Seoul, Korea in 1982, and the Ph.D. degree in mechanical engineering from the Georgia Institute of Technology, Atlanta, GA, in 1991.

From 1991 to 1995, he was on the Research Staff at Oak Ridge National Laboratory, Oak Ridge, TN. He is currently an Associate Professor in the Department of Mechanical Engineering, KAIST, Daejon, Korea. His current research interests include medical robots, haptic devices, telerobotics, human-robot interface, entertainment robots, and parallel manipulators.

Dr. Kwon is a member of KSME and ICASE.

Blake Hannaford (S'82–M'84–SM'01) received the B.S. degree in engineering and applied science from Yale University, New Haven, CT, in 1977, and the M.S. and Ph.D. degrees in electrical engineering from the University of California, Berkeley, in 1982 and 1985, respectively.

Before graduate study, he held engineering positions in digital hardware and software design, office automation, and medical image processing. At Berkeley, he pursued thesis research in multiple target tracking in medical images and the control of time-optimal voluntary human movement. From 1986 to 1989, he worked on the remote control of robot manipulators in the Man-Machine Systems Group in the Automated Systems Section of the NASA Jet Propulsion Laboratory, California Institute of Technology, Pasadena. He supervised that group from 1988 to 1989. Since 1989, he has been at the University of Washington, Seattle, where he has been Professor of Electrical Engineering since 1997, and served as Associate Chair for Education from 1999 to 2001. His currently active interests include haptic displays on the internet, and surgical biomechanics.

Dr. Hannaford was awarded the National Science Foundation's Presidential Young Investigator Award and the Early Career Achievement Award from the IEEE Engineering in Medicine and Biology Society. He is the founding editor of *Haptics-e, The Electronic Journal of Haptics Research*.