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Multiple Manipulator Cooperative Control using Disturbance Estimator and Consensus Algorithm

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***Abstract*— In this paper the Disturbance Estimator(DE) and the consensus algorithm are applied for the purpose of multiple manipulator cooperative control. The works in this paper are separated into the following two parts. As the first part, individual manipulator control is addressed. By means of the DE, unknown external disturbance is estimated without any force sensors. Moreover, output disturbance and the model difference between an actual plant and a desired plant are also estimated. As a result, total disturbance compensation and dynamics shaping are achieved by DE feedback control. As the second part, multiple manipulator stabilization is addressed. By means of 2nd order consensus algorithm, multiple links are considered to have a spring damper characteristics. Thus, even though different disturbances are applied to the links, stabilized manipulation is achieved. Simulation and experimental test using multiple links validate proposed cooperative manipulator control methods.**

I. Introduction

In the field of robotic manipulator control, numerous research has been conducted during several decades, and such researches can be categorized into following two central issues: reference tracking control and enhancing robustness to the disturbance. In the reference tracking control, past methods just using the inverse dynamics not only require much computation time but also are vulnerable to unknown external disturbances [1]. Due to the above disadvantages and increased demands for precise manipulator control, various approaches have been proposed. For example, robust control [2], parameter estimation techniques [3], model referenced control [4], iterative learning control [5], neural-fuzzy networks control [6] and optimal control [7], etc. Nowadays, even though the performance of manipulators has been enhanced through such varied approaches, when considering that the manipulators interact with objects and environments, further studies are required for immediate internal and external disturbance compensation.

In general, in order to measure the disturbance, force sensors or strain gauges are attached on the each actuator and link. However, disturbance compensation using force sensors has several drawbacks such as cost, sensing bandwidth and installation space. Especially for the surgical manipulators, infection is also one of the drawbacks. Thus, compensation methods do not require any force sensors are preferred. One of the well known solutions for the force sensorless disturbance estimation is the state feedback observer. Nicosia addressed disturbance observation and compensation for the flexible joint robots [8], [9]. One of the others is the disturbance observer [10], [11]. By using a part of an inverse transfer function and a low pass filter, the disturbance torque is estimated. In addition to such observers, M. Hou et al. proposed disturbance estimation with unknown input by using an equivalent system description [12]. Even though the disturbance is eliminated by using above disturbance observers, in the case the system model has parameter uncertainty and fluctuation, deterministic estimation results contain error continually. In order to solve such problems, many researches are executed with on-line parameter estimation methods. However, using on-line parameter estimation for disturbance estimation causes more complexity and computation time. Focused on such inappropriate phenomena, the DE is introduced in the present paper, and by using the DE, not only disturbance estimation but also disturbance compensation and plant dynamics shaping are achieved simultaneously. In addition to above problems, recent demands on the manipulator control are not only remaining on individual manipulator control but require more interactions and cooperations among manipulators. In the field of multi-agent system, consensus control has been introduced as a concept of the coincidence. Wei Ren studied consensus algorithms for single and double integrator dynamics, and shown asymptotic consensus under the varied input and measurement conditions [13], [14]. The formation control of UAVs and multiple mobile robots is also studied [15], [16]. In the field of multiple manipulator control, in terms of cooperation stability, corresponding sets of links or joints need to be controlled under proper conditions. Thus, this paper introduces consensus control into the multiple manipulator control. As a result, each corresponding links or joint are endowed with spring damper characteristic. In this paper, we consider the problems of individual manipulator control and multiple manipulator cooperation. For the individual manipulator control, an integrated control that consists of a conventional Proportional-Derivative(PD) controller and the DE is proposed. By using the disturbance estimator, unknown external disturbance is estimated, and compensated. In addition to the disturbance compensation, for the purpose of enhancing robustness to the system against the parameter fluctuation and uncertainty, this paper introduces reference model based system dynamics shaping by using the DE.

This paper is organized as follows. In section II, the necessities of the DE and the consensus algorithm in multiple manipulator control are presented. Section III explains the construction and the idea of the DE. In section IV, dynamics shaping and the DE design method are addressed. The concept of the consensus algorithm and advantages in multiple manipulator control are discussed In section V. Section VI describes the simulation and experimental results. Finally, the conclusion is made in section VII.

II. Background on Multiple Manipulators Cooperative Control

A. Disturbance Estimator

By the Euler-Lagrange equations, the motion of an n-link manipulator is described as follows [17]:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+F\dot{q}+g(q)+D(q)=u \qquad (1)$$

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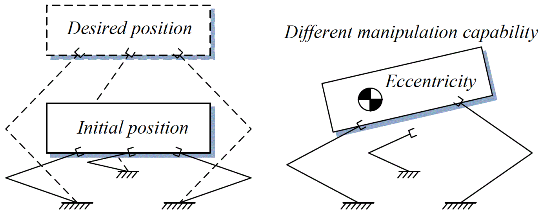

Fig. 1. Inappropriate phenomena in multiple manipulator cooperation.

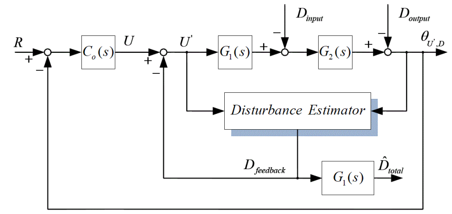

Fig. 2. Disturbance compensation system with the disturbance estimator.

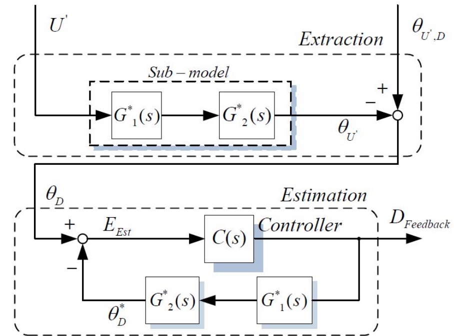

Fig. 3. The structure of the disturbance estimator.

where the matrix $M(q) \in \mathbf{R}^{n\times n}$ represents the inertia matrix, and the matrix $C(q,\dot{q})\dot{q} \in \mathbf{R}^n$ represents the vector of Coriolis and centrifugal force. The matrix $F \in \mathbf{R}^{n\times n}$ is the diagonal matrix of viscous friction coefficients, $g(q) \in \mathbf{R}^n$ is the vector of gravitational torques, $q \in \mathbf{R}^n$ is the vector of joint variables, and $u \in \mathbf{R}^n$ represents the vector of joint torques. In the independent manipulator control, by using the joint torques as follows:

$$u = M(q)q_d + C(q,\dot{q})\dot{q} + F\dot{q} + g(q) + D(q) \tag{2}$$

where $D(q)$ is the disturbance, the combined system given by (1) and (2) reduces to

$$\ddot{q} = q_d \tag{3}$$

where q_d represents desired $\ddot{q}$. By cancelation of nonlinear terms and the disturbance, the system (1) is changed into an uncoupled double integrator system. Such result signifies the system (2) is linear and decoupled. Thus, each desired input q_d can be designed to control a SISO linear system. The above inverse dynamics approach is one of the ideal methods in n-link manipulator control. However, obtaining exact parameters and nonlinearity is hard to achieve, and the system model has a parameter fluctuation. In order to overcome such problems, this paper proposes the DE. By means of the DE, total disturbance is estimated based on a model inside of the DE, and by using feedback control, total disturbance is compensated. In addition to disturbance compensation, DE shapes the plant dynamics into the desired model. On account of continuing dynamics shaping action, parameter uncertainty and fluctuation problems are solved. Moreover, the manipulator controller can be designed based on the known desired model.

B. Consensus Algorithm

Multiple manipulator cooperation enhances the effectiveness in required task by means of increased dexterity, loading capacity, and handling ability. However, there exists some inappropriate phenomena. e.g., when the manipulators raise an object, just controlling the position of the end-effector causes an unbalancing problem due to the difference of manipulation capability and the eccentricity of an object. Moreover, external disturbances or shocks cause unbalancing also (see Fig.1). In terms of multiple manipulator cooperation, such phenomena destabilizes the cooperative work. Thus, in order to get advantages of cooperation, agreement among the manipulators is necessary. For harmonious manipulator cooperation, the present paper gives a spring damper property among the manipulators by using the consensus algorithm.

III. Immediate Disturbance Estimation and Compensation by using Disturbance Estimator

In this section, the DE is addressed in terms of following two purposes: disturbance estimation and disturbance compensation. A general disturbance compensation system is depicted in Fig.2, and the detailed structure of the DE is depicted in Fig.3. The actual plant is represented by $G_1(s)$ and $G_2(s)$, and input disturbance(D_{input}) is applied. In order to validate total disturbance compensation, output disturbance(D_{output}) is also applied. The disturbances D_{input} and D_{output} can be any kind of disturbance, e.g., load torque(force), Coriolis and centrifugal torque, viscous friction, gravitational torque, parametric fluctuation or any combinations of them. In the present section, we assume that the plant dynamics $G_1(s)G_2(s)$ is same to the sub-model $G_1^*(s)G_2^*(s)$ (see Fig.3). However, problem solving on the parameter uncertainty and fluctuation is more desirable in the robotic manipulator control. Thus, section IV addresses the plant dynamics shaping with disturbance compensation using $G_1^*(s)G_2^*(s)$ which is different from actual plant.

A. Basic Concept of Disturbance Estimator

The DE consists of an extraction part and an estimation part. The two parts are cascade-connected.

1) Extraction part: The composition of the extraction part is same to the actual plant model. However, it does not have any disturbances. Thus, the extraction part calculates the system output generated by the input disturbance and the output disturbance as follows:

$$\theta_{U',D}(s) = G_1(s)G_2(s)U'(s) - G_2(s)D_{input} - D_{output} \tag{4}$$

$$\theta_{U'}(s) = G_1^*(s)G_2^*(s)U'(s) \tag{5}$$

The output(θ_D) of the extraction part is obtained by subtracting the plant output($\theta_{U',D}$) from the sub-model output($\theta_{U'}$) (see Fig.3). When the plant model is same to the sub-model, θ_D is obtained as follows:

$$\theta_D = G_2(s)D_{input} + D_{output} \tag{6}$$

2) Estimation part: The estimation part calculates the estimation result by using a feedback control loop. The reference signal of the feedback control loop is output(θ_D) of the extraction part. When the feedback loop is stable, in order to make θ_D^* follow θ_D, the output of the controller must be equal to total disturbance with the same unit of the input of $G_1(s)$. Thus, designing the DE can be completed by making the estimation part asymptotically stable. By means of error dynamics, the error transfer function is obtained as follows:

$$\frac{E_{Est}(s)}{\theta_D(s)} = \frac{1}{1+C(s)G^*(s)} \tag{7}$$

where $G(s) = G_1(s)G_2(s)$, $G^*(s) = G_1{}^*(s)G_2{}^*(s)$. When we have a perfect plant model, simply designing denominator of the error transfer function (7) as a Hurwitz polynomial, asymptotically stable total disturbance estimation is made. In addition, the DE dose not need multiplication of inverse transfer functions.

B. Disturbance compensation

As depicted in Fig.2, disturbance compensation is made by feedback of estimated total disturbance($\hat{D}_{Feedback}$). In order to verify the asymptotically stable condition of the controller, the transfer function from D_{input} to $\theta_{U',D}$ and from D_{output} to $\theta_{U',D}$ are obtained as follows:

$$\frac{\theta_{U',D}(s)}{D_{input}(s)} = -\frac{G_2(s)}{1+C(s)G(s)} \;\;,\;\; \frac{\theta_{U',D}(s)}{D_{output}(s)} = -\frac{1}{1+C(s)G(s)} \tag{8}$$

Asymptotically stable total disturbance compensation is also achieved by designing denominator of the error transfer functions (8) as a Hurwitz polynomial. However, if the plant is unstable and(or) non-minimum phase system, above design methods are not sufficient to determine the stability of the system. More detailed controller design method will be discussed in the following section.

IV. Plant Dynamics Shaping

In this section, we consider the situations that the actual plant has parameter fluctuation during the operation and(or) the model we have is not same to the actual plant. In such case, designing controller needs more complicated control techniques and computations. Thus, continual shaping of the plant dynamics into a desired model is one of the reasonable methods.

A. Internal Model Stability

In order to achieve above purposes, internal stability needs to be considered. From Fig.4, four sensitivity functions are obtained as follows:

1) Nominal complementary sensitivity

$$T_o(s) = \frac{Y(s)}{U(s)} = G(s)\frac{1+G^*(s)C(s)}{1+G(s)C(s)} \tag{9}$$

2) Nominal sensitivity

$$S_o(s) = \frac{Y(s)}{D_{output}(s)} = \frac{-1}{1+G(s)C(s)} = -(1-Q(s)G(s)) \tag{10}$$

3) Nominal input disturbance sensitivity

$$S_{io}(s) = \frac{Y(s)}{D_{input}(s)} = \frac{-G_2(s)}{1+G(s)C(s)} = -(1-Q(s)G(s))G_2(s) \tag{11}$$

4) Nominal control sensitivity

$$S_{uo}(s) = \frac{U^*(s)}{D_{output}(s)} = \frac{-C(s)}{1+G(s)C(s)} \triangleq -Q(s) \tag{12}$$

Noting that disturbance compensated unstable plant will be still unstable, thus (9) is neither a tracking problem nor a regulation problem. Hence, we design the controller in the DE by using (10)-(12) with affine parameterization [18], [19], and following controller design method will give us a set of possible solutions. In order to demonstrate comprehensive controller design, we assume the plant

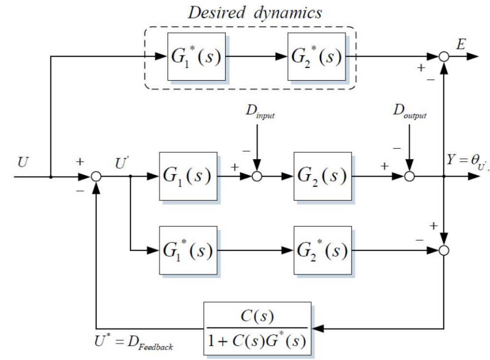

Fig. 4. Dynamics shaping and disturbance compensation.

is unstable and non-minimum phase. The transfer functions $G^*(s)$ and $G(s)$ represent desired dynamics and actual plant dynamics, respectively. The established goal is making the actual plant model act as same to the desired model with total disturbance compensation. Let us assume the plant dynamics and $Q(s)$ as follows:

$$G_1(s) = \frac{B_d(s)}{A_d(s)} \;,\; G_2(s) = \frac{B_u(s)}{A_u(s)} \;,\; Q(s) = \frac{\tilde{P}(s)}{\tilde{E}(s)} \tag{13}$$

where the subscript d and u represent an unstable polynomial and a stable polynomial, respectively. Using (12) and (13), the controller is obtained as follows:

$$C(s) = -\frac{Q(s)}{1-Q(s)G(s)} = \frac{\tilde{P}(s)}{\tilde{E}(s)-\bar{P}(s)B_d(s)B_u(s)} \tag{14}$$

Theorem 1: From (10)-(14), necessary and sufficient conditions for the existence of the controller are given as follows:

(i) The zeros of $\tilde{E}(s)$ lie in the desirable(stable) region.
(ii) $A_u(s)$ is a factor of $\tilde{P}(s)$, i,e. there exists a $\bar{P}(s)$ such that $\tilde{P}(s) = A_u(s)\bar{P}(s)$
(iii) $A_u(s)$ is a factor of $1-Q(s)G(s)$

Proof: The above statements are verified as follows:

(i) From (12), stability of $Q(s)$ is necessary for internal stability.
(ii) From (10), undesirable poles of $G(s)$ should be zeros of $Q(s)$.
(iii) From (11), undesirable poles of $G_2(s)$ should be zeros of $1-Q(s)G(s)$.

■

B. Controller Design

Based on Theorem.1 the controller is designed as follows. From the condition (i), $\tilde{E}(s)$ is stable. From (ii), $A_u(s)$ is a factor of $\tilde{P}(s)$. Thus, there exists $\bar{P}(s)$ such that

$$Q(s)G(s) = \frac{\tilde{P}(s)}{\tilde{E}(s)}\frac{B_d(s)B_u(s)}{A_d(s)A_u(s)} \tag{15}$$

$$\tilde{P}(s) = A_d(s)A_u(s)\bar{P}(s) \tag{16}$$

From (iii),

$$1-Q(s)G(s) = 1-\frac{\tilde{P}(s)B_d(s)B_u(s)}{\tilde{E}(s)A_d(s)A_u(s)} = \frac{\tilde{E}(s)-\bar{P}(s)B_d(s)B_u(s)}{\tilde{E}(s)} \tag{17}$$

and, $(1-Q(s)G(s))G(s)$ must be stable. Hence there exists a $\bar{P}(s)$ such that

$$\tilde{E}(s)-\bar{P}(s)B_d(s)B_u(s) = \bar{L}(s)A_d(s)A_u(s) \tag{18}$$

The above equation (18) is changed into the following equation

$$\bar{L}(s)A_d(s)A_u(s)+\bar{P}(s)B_d(s)B_u(s) = \tilde{E}(s) \tag{19}$$

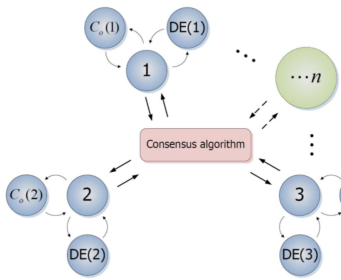

Fig. 5. multiple manipulator control with consensus algorithm.

$$\Rightarrow L^*(s)A_c(s)A_u(s)+P^*(s)B_d(s)B_u(s)=\bar{E}(s) \tag{20}$$

where $\bar{E}(s)=\tilde{E}(s)/A_d(s)$, $P^*(s)=\bar{P}(S)/A_d(s)$, $L^*(s)=\bar{L}(s)/A_c(s)$, $\bar{E}(s)$ is a desired pole allocation equation, and A_c is a design parameter of the controller. For example, if the controller is required to have integral action, $A_c(s)$ can have an integrator. From (19) and (20), we have $L^*(s)$ and $P^*(s)$, and from (14), (16)-(20), a possible set of the controller in the DE is obtained as follows:

$$\begin{aligned} C(s) &= \frac{\tilde{P}(s)}{\tilde{E}(s)-\bar{P}(s)B_d(s)B_u(s)} = \frac{P^*(s)A_d(s)A_u(s)A_d(s)}{L^*(s)A_c(s)A_d(s)A_u(s)} \\ &= \frac{P^*(s)A_d(s)}{L^*(s)A_c(s)} \end{aligned} \tag{21}$$

Remark 4.1: In the case of unstable and non-minimum phase system, direct unstable pole-zero cancellation check should be performed analytically, prior to implementation.

Remark 4.2: By using the controller which satisfies above conditions (i)-(iii), the DE can be used for pre-stabilization.

As the next step, in order to validate dynamics shaping, we obtain the error dynamics $E(s)$ as follows:

$$E(s) = U(s)G^*(s)-Y(s) \tag{22}$$

$$\frac{E(s)}{U(s)} = G^*(s)-G(s)\frac{1+G^*(s)C(s)}{1+G(s)C(s)} = \frac{G^*(s)-G(s)}{1+G(s)C(s)} \tag{23}$$

From the condition of the controller design, the nominal sensitivity function (10) is stable, and the nominal input disturbance sensitivity function (11) is also stable, and G^* is a desired stable function. Thus, error dynamics (22) is stable.

Remark 4.3: Stable error dynamics represents stable dynamics shaping. Moreover, designing proper A_c in (21) guarantees asymptotically stable shaping and disturbance compensation simultaneously.

V. Multiple Manipulator Stabilization using Consensus Algorithm

Proceeding works enable to achieve individual manipulator total disturbance compensation and dynamics shaping. However, multiple manipulator cooperation requires not only individual stability but also cooperative stability. Thus, even though the DE compensates the total unknown disturbance, following situations need to be considered:

(i) In the cooperation, when the different disturbances are applied to some manipulators, some other manipulators will stray from their desired position or trajectory.

(ii) When the manipulators have different errors, generated control signals will be different to each others. Thus, their trajectory, velocity and acceleration will be different also.

(iii) When the manipulators are controlled independently, individual manipulator is not concerned with the status of others.

TABLE I

Link parameters used in the simulation

Parameter	Value	Unit
Torque coefficient(K)	0.0259	Nm/A
Moment of inertia(J)	0.0005	$Nm{\cdot}s^2/rad$
Viscous friction coefficient(B)	0.001	$Nm{\cdot}s/rad$

In order to solve above inappropriate situations, the 2nd order consensus algorithm is applied to the multiple manipulator control. Consider a multiple manipulator cooperative system as depicted in Fig.5. Where n represents the total number of manipulator, $C_o(i)$ represents a tracking controller of an ith manipulator, and $DE(i)$ is the ith DE, and we assume that every manipulators have state informations of the others. Thus, the structure is equivalent to the strongly connected graph. Based on the properties of graph theory, manipulators in Fig.5 are described as below.

A graph $G=(V,E)$ with n nodes consists of the vertex V and the edge E, where $V=\{v_1,\cdots,v_n\}$, $E\subseteq V\times V$. The adjacency matrix A and degree matrix D are defined as“follows” [20]:

$$A=a_{ij}=\begin{cases} 1 & if(v_i,\, v_j)\in E \\ 0 & else \end{cases} \tag{24}$$

$$D=d_{ij}=\begin{cases} \sum_j A_{ij} & if(i=j) \\ 0 & else \end{cases} \tag{25}$$

From (24) and (25) the Laplacian matrix L is obtained as $L=D-A$, and the 2nd order consensus algorithm is described as follows [21]:

$$\ddot{x}_i = \sum_{v_j\in N_i} K_p(x_j-x_i)+\sum_{v_j\in N_i} K_v(\dot{x}_j-\dot{x}_i) \tag{26}$$

$$\ddot{x} = -K_pLx-K_vL\dot{x} \tag{27}$$

where the neighborhood $N_i=\{v_j\in V:(v_i,v_j)\in E\}$, x_i represents value of the ith node, K_p and K_v represent positive definite stiffness and damping gains, respectively. As equation (27) demonstrates, where x is the angular position of the link, control signal is obtained as a unit of acceleration. Thus, adding (27) to the outer control signal U will directly control the acceleration (i.e., torque) of the manipulators. By means of applying 2nd order consensus algorithm to each manipulators, their movement is considered to be connected with each others by a spring and a damper. See [22] for more information and stability of the consensus algorithm.

VI. Simulation and Experimental Tests

In this section, proceeding works are validated by simulations and experimental tests. Disturbance estimation, compensation, dynamics shaping and stabilized multiple manipulator cooperation are demonstrated by simulations. In addition, stabilized multiple manipulator cooperation is compared with conventional PD control by the experimental tests.

A. Simulation Results

The simulations are executed based on a DC motor controlled link model. The overall structure and the model of the link are depicted in Fig.6. The transfer functions $G_1(s)$ and $G_2(s)$ are represented as follows:

$$G_1=K \quad , \quad G_2=\frac{1}{s(Js+B)} \tag{28}$$

By using the affine parameterization, a one of the proper controllers in the DE is obtained as follows:

$$C(s)=\frac{1.8[(80s+10)(s+2)]}{s(s+150)} \tag{29}$$

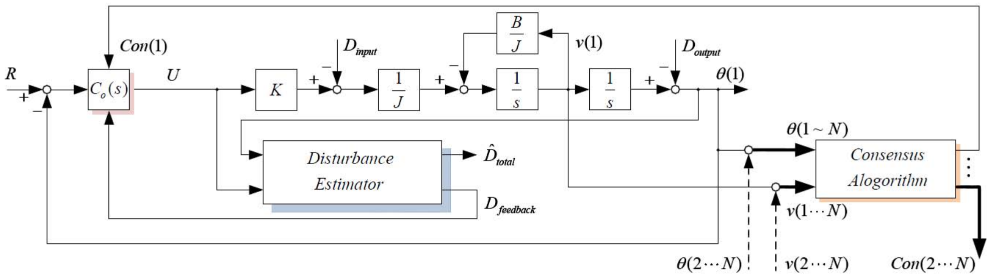

Fig. 6. Overall structure of multiple manipulator control system with the disturbance estimator and the consensus algorithm.

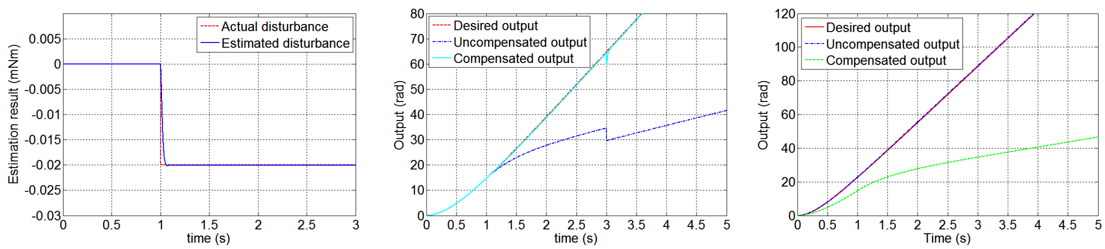

Fig. 7. Disturbance Estimation(left). Input and output disturbance compensation(center). Dynamics shaping(right).

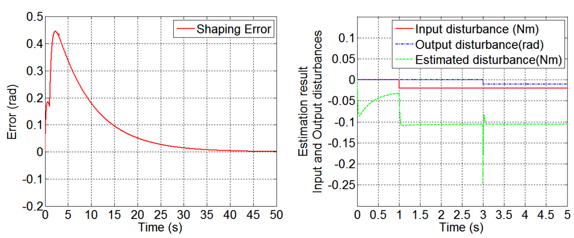

Fig. 8. Dynamics shaping error(left). Total disturbance estimation(right).

1) *Disturbance estimation:* Disturbance estimation is executed by using the open-loop link model in (28). Input disturbance ($D_{input} = 0.02$ (Nm)) is applied at 1 (sec), and the control signal U is given as 1 (A). As Fig.7(left) depicts, the designed controller (29) generates asymptotically stable estimation result.

2) *Disturbance compensation:* Input disturbance ($D_{input} = 0.02$ (Nm)) and huge output disturbance ($D_{output} = 5$ (rad)) are applied at 1 (sec) and 3 (sec), respectively. As Fig.7(center) depicts, compensated output tracks desired output asymptotically.

3) *Dynamics shaping:* For the dynamics shaping, the following parameters $K = 0.1$ (Nm/A), $J = 0.001$ $(Nm{\cdot}s^2/rad)$ and $B = 0.003$ $(Nm{\cdot}s/rad)$ are used as the desired plant. Input and output disturbances are also applied at 1 (sec) and 3 (sec), respectively. In Fig.7(right), response between 0 (sec) and 1 (sec) demonstrates that the actual plant is not same to the desired model. However, by using the disturbance estimator, asymptotically stable disturbance compensation and dynamics shaping is achieved as depicted in Fig.8(left). In addition to above results, the estimation result depicted in Fig.8(right) represents the DE estimates all the difference between the actual plant and desired plant. Thus, if the controller in the DE is stable and fast enough, not only the disturbances but also parameter uncertainty, fluctuation and non-linearity will be compensated.

4) *Multiple manipulator stabilization:* In Fig.6, a PD controller C_o is employed for link position control, and a consensus controller is located in the right side. The same desired trajectory is given to the three links as depicted in Fig.9 by a red solid line. However, different external step input disturbances 0.02, 0.09 and 0.04 (Nm) are applied at 1.5 (sec) to the link 1,2 and 3, respectively. In addition, the links have different parameters as listed in Table.II. When the manipulators are controlled by a conventional PD controller only, different responses are appeared due to the different link dynamics as depicted In the beginning of Fig.9(left). After 1.5 (sec), we can find discordance among desired trajectory and three links also. However, when the consensus algorithm is applied, the coincidence is achieved as depicted in Fig.9(center). Finally, when both the consensus algorithm and the DE are applied, different dynamics and external disturbance are compensated, and even though the different disturbances are applied to the each link, consensus controller makes links maintain a balanced position and velocity. As Fig.9(right) demonstrates, harmonic manipulation with the total disturbance compensation is achieved.

TABLE II
PARAMETERS USED IN THE MULTIPLE MANIPULATOR SIMULATION

Parameter	Link 1	Link 2	Link 3	Unit
Torque coefficient(K)	0.0159	0.0259	0.0459	Nm/A
Moment of inertia(J)	0.0005	0.0004	0.0003	$Nm{\cdot}s^2/rad$

B. Experimental test results

The experimental tests are executed by three links actuated by DC motors. Three links are lifting different weights such as 0, 0.165 and 0.279 (kgf), respectively. As the above simulation results demonstrated, the experimental results in Fig.10 also validate the DE compensation and the consensus control.

VII. CONCLUSION

This paper proposed multiple manipulator cooperative control using the Disturbance Estimator(DE) and the consensus algorithm. The DE estimates the input and output disturbances using an

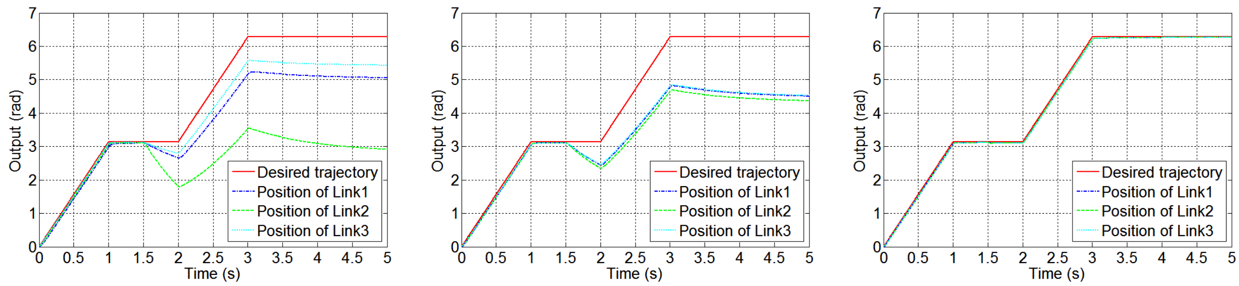

Fig. 9. Simulation results of multiple manipulator control without compensation(left). Consensus control(center). Consensus control with DE compensation(right).

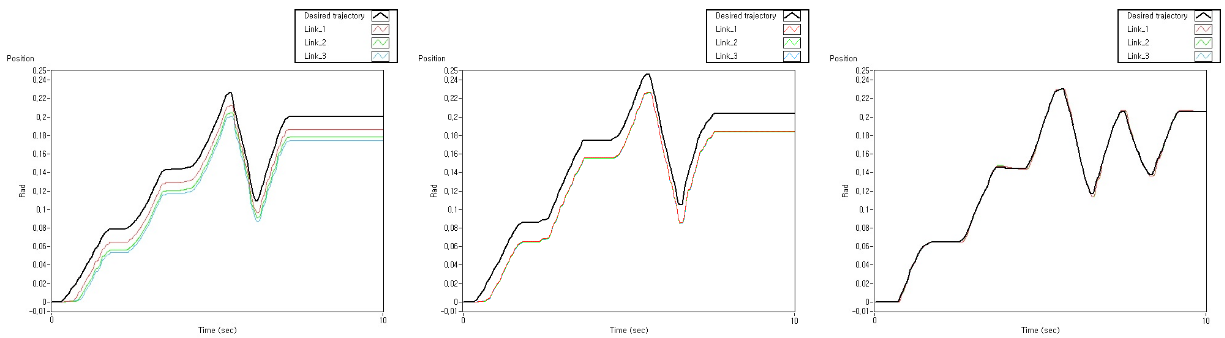

Fig. 10. multiple manipulator control without compensation(left). Consensus control(center). Consensus control with DE compensation(right).

input signal of the plant and an output state. By the estimation result, undesirable terms in the individual manipulator control such as Coriolis and centrifugal torque, viscous friction, gravitational torque and parametric fluctuation are compensated. Moreover, the disturbance estimator estimates not only external disturbances but also internal dynamics discordances. Thus, by using the feedback compensation, the DE makes actual plant act as same to the desired model. For the stabilized multiple manipulator control, we focused on the cooperative stability. By the consensus control, links are considered to have a spring damper characteristic. By means of consensus control and the DE, disturbance estimation, compensation, dynamics shaping and the consensus of the multiple manipulator are achieved successfully.

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