Sensory Feedback for High Dissymmetric Master-Slave Dexterity

Michel Cotsaftis and Erno Keskinen

Abstract: Conditions are discussed for operating a dissymmetric human master-small (or micro) slave system in best (large position gain-small velocity gain) conditions allowing higher operator dexterity when real effects (joint compliance, link flexion, delay and transmission distortion) are taken into account. It is shown that position PD feedback law advantage for ideal case no longer holds, and that more complicated feedback law depending on real effects has to be implemented with adapted transmission line. Drawback is slowdown of master slave interaction, suggesting to use more advanced predictive methods for the master and more intelligent control law for the slave.

Keywords: dexterous dissymmetric telerobotic system, transparency, passivity, signal distortion

I. Introduction

Demand in telerobotic systems replacing human direct action in factories and/or in hostile environment [1]-[3] has been increasing in recent years. More specifically, recent achievement in production of micro-components for micro-machines [4][5] has opened a new domain of investigation for microparts teleoperated assembly. Similarly, less invasive health care has been at the origin of micro-surgery[6] interventions with adapted tools, and space research is now concerned with development of small scale easier to launch robots for planet exploration. In all cases operations have to be driven in small or micro size world by nature different from meso scale operator world. Due to high dissymmetry between master and slave systems, specific phenomena related to their scale difference have to be taken care off[7]. For these dissimilar electrically linked stations, with polyarticulated mechanical structure to reproduce operator hand dexterity, two important conditions have to be satisfied at the same time for allowing the operator to reach optimum level of dexterity during manipulation. First a bilateral control should be constructed to provide the operator with natural force feedback feeling [8]-[11]. However, to increase dexterity, the control scheme should be carefully designed to account for disparity of system parameter values, especially as concerns the large inertia difference. Along this line, a position feedback bilateral control is compared to usual force feedback one[12] and resulting natural feeling for the operator are discussed. Second when dealing with real systems with joint compliance, link flexibility and transmission delay, the control should be designed so that both stability and transparency properties continue to be satisfied for acceptable quality exchange between stations[13], in a way similar to existing case of rigid tools with weak inertia and large stiffness (like mechanical plier). Because system dynamics cannot be completely suppressed, only an optimum is expectable as low enough gains are required in feedback loops for stability whereas transparency is improved by gain increase, and the optimum is the better as stability limit is larger. For rigid system with no delay between stations, its passivity insures stability when connected with any (passive) environment[14]. In quadrupole (applied force-velocity) form, impedance control[15] gives both master and slave stations preassigned dynamics regulating more appropriately energy exchange with exterior. When real physical properties (joint compliance, internal flexion and torsion modes, ..), and technical constraints (signal distortion from unperfect communication between stations and numerical processing inside stations), are taken into account[16], passivity no longer holds. For a (rigid master station + transmission line + rigid slave station)-system with PD feedback control law, passivity which is destroyed by delayed transmission, is restored by lossless transmission line[17]. However apparent real telerobotic systems maneuverability suggests that passivity condition may be too stringent, as verified by analysis of exact stability conditions for real (non passive) telerobotic system, and comparison to the ones for rigid (passive) system. If the two limits are close enough, intrinsic stability is not drastically modified by passivity loss, and impedance control approach extends to this case.

So stability limits for one DoF complete (master station + transmission line + slave station) system are analytically obtained in terms of (position gain, velocity gain)-parameters for the proposed PD feedback bilateral control laws. Over a large system parameter range the limits are not widely modified, and system parameters can be chosen to minimize passivity index for given PD law. As this conflicts with transparency condition which is an important quality index for telerobotic system ergonomy, only an optimum can result by minimizing impedance error with respect to desired system impedance with required transparency. But exactly as for rigid master-slave system where passivity is restored against transmission delay with lossless transmission line, one may research whether passivity can be restored for realistic compliant, deformable master-slave system by designing adapted transmission line coefficients. In this case, a more general feedback law than PD one is required, and in complete [feedback law + transmission line] parameter space, there exists a nonlinear analytical transformation projecting actual compliant deformable delayed telerobotic system onto a desired reference one with prescribed nominal parameters, and passive if rigid. Moving however from actual system to apparent rigid one for the operator is payed by response slowdown due to larger power reflexion coefficient, because of slower circulation time of informations between stations, indicating a physical limitation of this way of approach. Extension to full N-link dissymmetric telerobotic system is easily possible.

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II. Equations for telerobotic system

Station dynamics for one DoF telerobotic system, after compensation of potential term, are modelled in normalized quadrupole form in each station as

$$\tau_j(s)=M_j(s)v_j+F_{extj} \tag{1}$$

with articular velocity v_j, $(j=1,2)$ for master and slave respectively, generalized forces $F_{ext1} = -K_1F_{op}$, $F_{ext2} = -K_2F_{env}$ exerted by operator and environment, $K_j = N_{j,22}J_j$, input torques $\tau_j = C_j(s)^{-1} N_{j,-21}T_j$, linear transfer functions $M_j(s) = M_{0j}(s)[1+\Phi_j(s)]$ after elimination of all station state variables but articular ones, where $M_{0j}(s)$, $C_j(s)$ and $+\Phi_j(s)$ characterize station description level, and $N_{j,mn}=v_j^m(1+v_j^2)^{-n}$, see Fig.1.

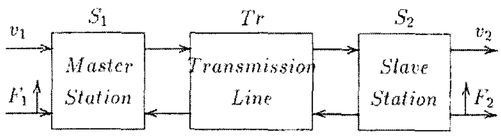

Fig. 1. Quadrupole representation of telerobotic master–Slave–transmission line system.

For rigid damped system, $M_{0j} = s+f_j$, $C_j = 1$, $\Phi_{rj}(s) = 0$, for compliant system $C_j(s) = C_{0j}(s) + v_j^2$, $C_{0j}(s) = \varepsilon s(s+f_{mj})$, $\Phi_{cj}(s) = N_{j,01}(s+f_{mj}).(s+f_j)^{-1} C_{0j}(s)^{-1} C_j(s)$ and $f_{aj} = B_{aj}/J_{aj}$, $f_{mj} = (B_{mj}+K_{vmj})/J_{mj}$, $f_j = N_{j,01}(f_{mj} + v_j^2 f_{aj})$, $v_j^2 = J_{aj}/r_j^2 J_{mj}$, $\varepsilon_j^{-1} = K_c/J_{mj}$, and viscous damping B_{kj}, articulation $(k=a)$ and motor $(k=m)$ inertia moment(or mass) J_{kj}, velocity gain in motor feedback loop K_{vmj}, compliance stiffness K_c ($\varepsilon_j = 0$ for rigid system), reduction factor r_j between motor and articular variables, extendable to multicompliant case. For internal flexion modes $\Phi_{fj}(s) = \Phi_{cj}(s) - N_{j,01}s\,(s+f_j)^{-1}\Phi_{dj}(s)$, with $\Phi_{dj}(s) = \lambda I^*_j \sum_k h_{jk}{}^2 s^2(s^2 + \xi_{jk}s + \lambda_{jk}\omega_{fj}^2)^{-1}$, with discrete eigenvalue spectrum λ_{jk} with adapted boundary conditions [18], eigenfunction $w_{jk}(x)$, $0 \le x \le 1$ normalized to segment length l_j, damping coefficient ξ_{jk} for mode k, and $h_{jk} = \int x w_{jk}(x)dx$, $\omega_{fj}^2 = E_j I_j \rho_j^{-1} l_j^{-4}$ the characteristic flexion frequency, I_j* a normalized moment of inertia and λ a number depending on flexion model. Torsion effects appear in higher nonlinear order terms, and series in Φ_{dj} rapidly converges as h_{jk} decay very fast and λ_{jk} grow like $(k\pi)^{-4}$[19], requiring few terms for good numerical approximation.

The problem is to organize both input torques $\tau_j(s)$ and bilateral transmission line between stations in order to favourize passivity, or at least stability, and transparency of complete system. These two properties are required to give the operator the possibility to take full advantage of all the dof in an ergonomic way, ie to proceed with highest dexterity often needed for delicate operations. It should also be mentionned that this is a prerequisite for using finer sensors in that they have to fit with operator actual capability over his operating frequency band. For master and slave stations first and in rigid case, at equilibrium one should have $F_1 = \alpha F_2$, $x_2 = \beta x_1$ with $\alpha >> 1$, $\beta << 1$ but $\alpha\beta$ is not fixed. So a feedback should be constructed with the two differences $F_1 - \alpha F_2$ and $x_2 - \beta x_1$, and should include a PD feedback and a force feedback term to restore reversibility for large r_j systems by changing in eqn(1) the inertia to an "apparent" smaller one[20] to increase sensibility. Including this term by changing definitions of J_{kj}, The usual force feedback reads

$$\tau_1 = -\alpha F_2 - k_f(\alpha F_2 - F_1),$$
$$\tau_2 = k_P s^{-1}(\beta v_1 - v_2) - k_V v_2 \tag{2a}$$

whereas position feedback takes the form

$$\tau_1 = k_P s^{-1}(v_2\beta^{-1} - v_1) - k_V v_1 - F_1,$$
$$\tau_2 = F_1\alpha^{-1} + k_f(F_1\alpha^{-1} - F_2) \tag{2b}$$

with the three gains (k_P, k_V, k_f) respectively for position, velocity and force whose stability domain is to be determined.

As it will be useful later, the transmission line can be represented by its scattering matrix $S(s) = \mathrm{Tab}\{S_{ij}(s)\}$, $(i,j = 1,2)$, and $V_+ = SV_-$, with $V_\pm = \mathrm{col}(F_1 \mp k_0v_1, F_2 \pm k_0v_2)$, k_0 a scale factor between force and velocity. Its coefficients S_{ij} are only required to satisfy the condition $S_{ij}(0) = 1 - \delta_{ij}$, and transmission part is passive when the condition

$$\mathrm{Sup}_{\omega\in\Sigma} |\lambda^{1/2}[S^\times(i\omega)S(i\omega)]| \le 1 \tag{3}$$

holds[21]. With $M_{\varepsilon\varepsilon'} = (1+\varepsilon S_{11})(1+\varepsilon' S_{22}) - \varepsilon\varepsilon'' S_{12}S_{21}$, $(\varepsilon, \varepsilon' = \pm 1)$, one then gets for instance

a) for instantaneous connection time, $S_{ij}(\omega) = 1 - \delta_{ij}$, ie $M_{--} = M_{++} = 0$, $M_{-+} = M_{+-} = 2$

b) for delay connection time T, $S_{11} = -S_{22} = -\tanh(sT)$, $S_{12} = S_{21} = (\cosh(sT))^{-1}$, and eqn(3) is not satisfied

c) for modified lossless transmission line with $S_{ii} = 0$, $S_{ij}(s) = d(s)\exp{-sT} = \exp{-\varphi(sT)}$, ie $M_{\varepsilon\varepsilon'} = 1 - \varepsilon\varepsilon' S_{ij}^2$, $d(s)$ a corrector (a low passband filter), eqn(3) is satisfied with condition $\mathrm{Sup}_{\omega\in\Sigma} |d^*(i\omega)d(i\omega)| \le 1$, including $d = 1$.

III. Stability analysis

Considering first the simplified case where S = I, and writing $F_2 = \Omega_e^2(x_2 - x_e)$ to stress impedance equivalence of environment on which slave station is acting, and taking $x_e = 0$, eqns(1) with feedback laws (2ab) become respectively

$$\frac{x_1}{F_1} = \frac{\mu k}{s^2 + d_1 s + \dfrac{\mu k\alpha\beta\,\Omega_e^2\omega_P^2}{s^2 + (d_2+\omega_V)s + \Omega_e^2 + \omega_P^2}} \tag{4a}$$

$$\frac{x_1}{F_1} = \frac{\omega_P^2 k}{\alpha\beta}\,\frac{1}{s^2 + (d_1+\omega_V)s + \omega_P^2}\,\frac{1}{s^2 + d_2 s + k\Omega_e^2} \tag{4b}$$

with d_j the total damping in each station (physical + feedback), $\mu = J_{m1}/J_{m2}$ the inertia (or mass) ratio between station, $k = 1 + k_f$, and writing for convenience $k_P = \omega_P^2$, $k_V = \omega_V$.

For large position gain (ie $\omega_P >> 1$) corresponding to the most sensitive case, the two transfer functions (4ab) respectively write

$$\frac{x_1}{F_1} = \frac{k}{\mu^{-1}(s^2 + d_1 s) + k\alpha\beta\Omega_e^2} \quad \frac{x_1}{F_1} = \frac{k}{\alpha\beta(s^2 + d_1 s + k\Omega_e^2)} \tag{5ab}$$

showing that the environment is perceived with amplified dynamics by a factor μ^{-1} in the usual case of force feedback leading to lesser dexterity for the operator than with position feedback control law.

However, it should also be ascertained that stability is not affected by choosing this law. Stability is determined by pole location of discriminant of eqns(4ab) in complex plane. Here, instead of getting conditions on the gains from Hurwitz type expressions, a more general method will be used. It is based on the remark that the determinant equation $\Delta(\omega,\gamma) \equiv X(\omega,\gamma) + iY(\omega,\gamma) = 0$, with $s = -\gamma + i\omega$, can be written more precisely $X(\omega,\gamma,\omega_P,\omega_V) = Y(\omega,\gamma,\omega_P,\omega_V) = 0$, ie as a transformation of the complex (ω,γ)-plane to the (ω_P,ω_V)-gain plane. As it is here linear in these last parameters from linearity of the feedback law in the gains by construction, this gives an explicit parametric representation of equal decay $(\gamma = \gamma_0)$-curves in the gain plane, and the strict stability domain corresponds in the gain plane to the transform of the domain limited by zero margin curve $\gamma_0 = 0$ and the infinitely damped curve $\gamma = \infty$.
Direct application to the denominator of eqns(4ab) leads to the curves

$$\begin{aligned} \omega_P^2(\omega) &= \frac{(\omega^2 + d_1^2)(\omega^2 - \Omega_e^2)}{\omega^2 + d_1^2 - \mu\alpha\beta k\Omega_e^2} \\ \omega_V(\omega) &= -d_2 + \mu\alpha\beta k\Omega_e^2 d_1 \frac{\omega^2 - \Omega_e^2}{\omega^2(\omega^2 + d_1^2 - \mu\alpha\beta k\Omega_e^2)} \end{aligned} \quad (6a)$$

and

$$\omega_P^2 = (d_1 + \omega_V)^2 / 4 \qquad k \le d_1^2 / 4\Omega_e^2 \quad (6b)$$

in parametric and explicit form respectively. Analysis of these curves, see Fig.2, shows that stability domain for eqn(6a) includes for $\mu\alpha\beta k < 1 + d_1^2/\Omega_e^2$ the domain $\omega_P^2 \to \infty$, $\omega_V \to 0$, whereas this is forbidden by condition (6b).

So operation in useful high position gain case demands a large velocity gain for stability with position feedback law, which in turn contributes to destabilize the closed loop system unless high quality sensors are used . The upper bound for force gain k is also much lower and makes this control law less attractive overall.

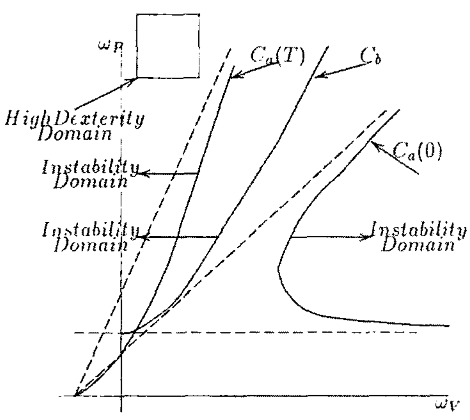

Fig. 2. Stability limits (ω_P,ω_V > 0) for :

(1)- No-Delay force feedback control law C_a(o)

(2)- Delay T force feedback control law C_a(T)

(3)- Any Delay position feedback control law C_b with high dexterity domain.

However the situation drastically changes if due to working conditions a delay T is occurring in the transmission line between stations so that $v_1 = v_2 \exp{-sT}$, $F_2 = F_1 \exp{-sT}$ (case b above). In this case eqns(6a) become

$$\begin{aligned} \omega_P^2(\omega) &= \frac{(\omega^2 + d_1^2)(\omega^2 - \Omega_e^2)}{\omega^2 + d_1^2 - \mu\alpha\beta k\Omega_e^2(d_1 \sin 2\omega T/\omega + \cos 2\omega T)} \\ \omega_V(\omega) &= -d_2 + \mu\alpha\beta k\Omega_e^2 \\ &\quad \frac{(\omega^2 - \Omega_e^2)(d_1 \cos 2\omega T - \omega^2 \sin 2\omega T/\omega)}{\omega^2[\omega^2 + d_1^2 - \mu\alpha\beta k\Omega_e^2(d_1 \sin 2\omega T/\omega + \cos 2\omega T)]} \end{aligned} \quad (7a)$$

with the possibility of new poles from the oscillatory behavior of the denominator when T and $\mu\alpha\beta k\Omega_e^2$ are large enough. As they are always in even number, they induce new unstable domains in the first quadrant, see Fig. 2, including the useful high position-low velocity gain domain along the ω_P –axis, as soon as $\mu\alpha\beta k\Omega_e^2T^2 > 2.5$ typically. Then there might be less advantage to the force feedback control, and the more as with delay T, eqn(4b) becomes

$$\frac{x_1}{F_1} = \frac{\omega_P^2 k \exp{-2sT}}{\alpha\beta} \frac{1}{s^2 + (d_1 + \omega_V)s + \omega_P^2} \frac{1}{s^2 + d_2 s + k\Omega_e^2} \quad (7b)$$

showing no change in the stability limits. From the curves, the choice is depending on operating gain domain fixed by station parameters and on sensed frequency band linked to operator sensitivity. On the other hand the role of other parameters such as the transmission line ones has to be fixed on a more general setting. In eqns(2ab) for previous feedback laws, velocity and force from the other station are transformed by transmission line and their value determined from scattering matrix S above. Though complete analysis is depending on specific considered case, observation of cases b) and c) for S suggests larger stability domain in case c), as the pure dephasor slows down some signal components so that passivity of transmission matrix can be maintained. The corresponding S matrix is characterized by the property that for $\omega \to 0$, $S_{jj} \to 0$ but $S_{jk} \neq 0$. On the other hand, as more generally slave station interacts with environment, stability condition is not sufficient and more restrictive passivity condition preserved for interaction with passive environment is required.

IV. Passivity preserving impedance matching

Passivity property extends when one of system subparts becomes nonpassive, and system distance to passivity is not known. If transfer function $H_k(s)$, $(k=1,2..n)$, satisfies $\Re e(H_k(i\omega)) \ge -a_k$, $0 \le a_k < 1$, the system is stable[22] but not passive. Shifted system with transfer function $H+A = T\,[\mathrm{diag}(H_k + a_k)]\,T^{-1}$, $|A| \le 1$ is passive, with $a = \mathrm{col}(a_1, a_2, .. a_n)$ measuring distance to passivity[23] and value of environment parameters it can be connected with for global passivity. Easier sufficient conditions are obtained[24] with $a = \max_j [a_j]$. For compliant case, one finds $-a_{max} = \mathrm{Inf}\,\{0, f_j - f_{mj}^{-1}\varepsilon_j^{-1}(1 + v_j^2)^{-1}(2v_j^2 - \varepsilon_j f_{mj}^2)^2(4v_j^2 - \varepsilon_j f_{mj}^2)^{-2}\}$, and a more complicated expression when adding flexion terms. On the other hand, telerobotic system should also be transparent enough for easier manipulability from ergonomic criteria. This imposes impedance matrix $Z(s)$ (the coefficients of v_1 and $-v_2$ in eqns(4)) to be closest to a desired (passive) one $Z_{des}(s)$ = Tab | $Z_{ij,des}(s)$ | with

$$Z_{11,des}(s) = M_1{}^*+k^*(s), \quad Z_{12,des}(s) = \beta k^*(s)$$
$$Z_{21,des}(s) = \mu \alpha^{-1} k^*(s), \quad Z_{22,des}(s) = M_2{}^* + \mu \beta\alpha^{-1} k^*(s) \quad (8)$$

with $M_j{}^* = s + f_j{}^*$, $k^*(s) = k_P{}^* s^{-1} + k_V{}^*$, $k_P{}^* = K^*/J^*$, $k_V{}^* = B^*/J^*$, obtained from desired dynamics with mass (or inertia) $J_j{}^*$, damping $B_j{}^*$, $(j=1,2)$ in each station, stiffness K^* and damping B^* of transmission line, and scaling factors g_1,g_2 for forces and velocities between stations. Then minimizing transparency error $d_T(k_P,k_V,\Omega_l)$ = | $Z(s) - Z_{des}$ $|_{L\infty(0,\Omega l)}$ over (k_P,k_V) belonging to shifted passivity domain by a gives "best" telerobotic system with PD feedback law, systematized with adapted tools[25].

But better approach is to get direct matching of $Z(s)$ to $Z_{des}(s)$ by using for convenient choice large existing freedom in scattering matrix coefficients only restricted to satisfy $S_{ij}(0) = 1 - \delta_{ij}$ and eqn(3). Including scaling factors α,β in impedance matrix $Z(s)$, the problem is to solve $Z(s) = Z_{des}(s)$ for all s. This only gives three relations for $S_{ij}(s)$, $(S_{12} = S_{21})$, so for designing transmission line to include delay or distortion effects another available function is needed, which is here the feedback law $k(s)$. So at least in principle it is possible to exactly match the actual system onto the desired one by determining the four functions $\{S_{ij}(s), k(s)\}$, $(S_{12} = S_{21})$, from the four equations $Z_{ij}(s) = Z_{des,ij}(s)$. The problem has been discussed for feedback law[26] $\tau_1(s) = -B_1v_1 - F_{1d}$ $\tau_2(s) = -B_2v_2 - k(s)(v_{2d} - v_2)$, slightly different from eqn(2a). Stability analysis shows as expected larger domain in gain space with pure dephasor in delayed case, and explicit solution for $Z(s) = Z_{des}(s)$ given by eqn(7) gives a feedback law which accounts for stations properties and reduces for low frequency to basic PD one[27]. As off-diagonal terms are not fixed, one can use this freedom to passivate the transmission line. Using eqn(3), this is obtained by imposing that $S_{12} = S_{21} \approx \omega^{-\kappa}$ with $\kappa < 1$ as $\omega \to \infty$. The very meaning of this mild decay condition guaranteeing passivity of matrix S is that any time an information is distorted by delay or another effect, the resulting power exchange between stations is lowered, as verified from mean reflected power expression $P_r = 1/4\ (F + k_0v)^T[1 - S^+S](F + k_0v)$, and the more as the frequency band where distortion occurs is larger, though possibly counteracted by filter $d(s)$ especially above Ω_l.

In conclusion, analysis of teleoperation system with small scale slave indicates that there is a specific advantage to use position feedback law when delay is small enough, because the system is stable in the high gain domain where it is operated with higher dexterity. Safer passivity condition is in general not met with non perfect transmission line between stations and transparency condition cannot also be satisfied if simple PD feedback law is used. On the contrary, fixing passivity and transparency properties as a prerequisite for dexterous manipulation, it is possible to satisfy both conditions by adapting transmission line structure and local feedback laws in slave and master stations, due to existence of transformation group between systems impedance, only accessible inside the complete set $[k(s),S_{ij}(s)]$ of system parameters. Then the actual system is projected onto a desired one according to well defined criteria. But reduction of actual telerobotic system to "ideal" one is payed by a slowdown of their dynamics to allow communication of relevant informations between stations. Physical reason is that only within this set one can satisfy information and power flux conservation demand between the two extremities of the chain, ie the quadrupoles (v_1,F_{ext1}), (v_2,F_{ext2}) in Fig.1. This is the direct consequence of chosing to preserve interaction quality and manipulability. It may be a serious drawback showing the limit of the present choice to meet both passivity and transparency without conflict as in previous studies. Anticipating local command structures inside stations with "reflex" type response and distributed intelligence could be an interesting alternative aside the more common telemonitoring [28][29] and virtual fixture generation[30] to improve again correlation between operator kinesthetic sense and feedback return from remote environment destroyed by all non ideal distortions (time delay, noise, ..).

References

[1] T.B. Sheridan : "Telerobotics," *Automatica* vol.25(4) p. 487, 1989

[2] J. Jenkins : "Space telerobotic systems : Applications and concepts," *Proc. Workshop on Space Telerobotics* JPL Pub. 87-13, vol.1,p.129,1987

[3] V.S. Yastrebov, G.A. Stepanov : "Underwater robot manipulator development," *Marine Technol. Soc. J.*, 12,p.1,1978

[4] L.S. Fan, Y.C. Tai, R.S. Muller : "Integrated movable micromechanical structures for sensors and actuators," *IEEE Trans. Electron Devices*, ED-35, p.724, 1988

[5] C.H. Ahn, Y.J. Kim, M.G. Allen : "A Planar variable reluctance magnetic micromotor with fully integrated stator and coils," *IEEE J. Micro-electromechanical Systems*, vol.II(4), p.165, 1993

[6] S.E. Salcudean, J. Yan : "Toward a force-reflecting motion-scaling system for microsurgery," *Proc. IEEE Intern Conf. On Robotics and Automation*, San Diego, p.2296, 1994

[7] P. Kallio, H.N. Koivo : "Micromanipulation : a survey of the application area," *Intern. Conf. On Recent Advances in Mechatronics, ICRAM'95*, Istanbul, Turkey, p.365, 1995

[8] Y. Yokokohji, N. Hosotani, T. Yoshikawa : "Analysis of maneuverability of micro-teleoperation systems," *Proc. IEEE Intern. Conf. On Robotics and Automation*, vol.I, p.237, 1994

[9] T. Sakaki, Y. Inoue, S. Tachi : "Tele-existence virtual dynamic display using impedance scaling with physical similarity," *Proc. 1993 JSME Intern. Conf. On Advanced Mechatronics*, Tokyo, Japan, p.127, 1994

[10] J.E. Colgate : "Robust impedance shaping telemani- pulation," *IEEE Trans. On Robotics and Automation*, vol.IX(4), p.374, 1993

[11] K. Kaneko, H. Tokashiki, K. Tanie, K. Komoriya : "Impedance shaping based on force feedback bilateral control in macro-micro teleoperation system," *Proc. IEEE Intern. Conf. On Robotics and Automation*, vol. II, p.853,

1997

[12] G. Burdea, J. Zhuang : "Dextrous telerobotics with force feedback – an overview : Part I : Human factors, Part II : Control and implementation," *Robotica*, vol.9, p.271 and p.291, 1991

[13] A.K. Bejczy : "Sensors, controls and man machine interface for advanced teleoperation," *Science*, 208(6) p.1327, 1980

[14] M. Handlykken, T. Turner : "Control system analysis and synthesis for a six dof universal force reflecting hand controller," *Proc. 19th IEEE Conf. on Decision and Control*, p.218, 1980

[15] N. Hogan : "Impedance control, an approach to manipulation : Part I - Theory, Part II - Implementation, Part III – Applications," *J. Dyn. Syst. Meas. Cont.*, vol.107, p.1, 1985

[16] M. Cotsaftis : "On the control of telerobotic systems," *Rep. UGRA*-1, CENFAR, France, 1989

[17] R.J. Anderson, M.W. Spong : "Bilateral control of teleoperators with time delay," *Proc. 27th Conf. on Decision and Control*, Austin, Texas, p.167, 1988

[18] T.J. Tarn, A.K. Bejczy, X. Ding : "On the modelling of flexible robot arms," *Rep. SSM-RL-87-08 and 88-11, Dept of Systems Science and Mathematics,* Washington Univ., Saint Louis, Miss.,1987-1988

[19] M. Cotsaftis : "La stabilisation des modes souples dans les systèmes flexibles," *Rep. UGRA*-315, CENFAR, France,1986

[20] J.J. Wlassich : "Nonlinear force feedback impedance control," *Master Thesis*, MIT, Cambridge, Mass. 1986

[21] J.E. Colgate : "The Control of dynamically interacting systems," *PhD Thesis*, MIT, Cambridge,1988

[22] C.A. Desoer, M. Vidyasagar : *Feedback Systems : Input-Output Properties*, Acad. Press, New-York,1975

[23] J.T. Wen : "Robustness analysis based on passivity," *Proc 27th IEEE Conf. on Decision and Control*, Austin, Texas,p.1207,1988

[24] P.J. Owens, D. Woods : "Reappraisal of the unconditional stability criteria for active two-ports networks in terms of s parameters," *Electr. Letters*, vol.6 (10), p.315,1970

[25] B.A. Francis : *A Course in H_∞ Control Theory*, Lecture Notes in Control and Information Sciences, 88, Springer-Verlag, Berlin,1988.

[26] R.J. Anderson : "A Network approach to force control in robotics and teleoperation," *PhD Thesis*, Univ. of Illinois Urbana-Champaign, 1989

[27] M. Cotsaftis : *Comportement et Contrôle des Systèmes Complexes*, Chap.V, Diderot, Paris, 1997

[28] Sukhan Lee, H.S. Lee : "An Advanced teleoperated control system : design and evaluation," *Proc. IEEE Intern. Conf. On Robotics and Automation*, vol.I, p.859, 1992

[29] T.B. Sheridan : *Telerobotics, Automation, and Human Supervisory Control*, The MIT Press, 1992

[30] L.B. Rosenberg : "The Use of virtual fixtures to enhance telemanipulation with time delay," *1993 ASME Winter Annual Meeting*, DSC-Vol.49, p.29, 1993

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