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Task Based Bilateral Control for Microsystems Application

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Design of a motion control system, convenient for a wide range of applications in industry, space, biology, medicine, particularly including more than one physics environment is very important. Well known control architectures like trajectory tracking, compliance control, interaction force control are scientific milestones which has common control task: to maintain desired system configuration. In this concept, motion control system can be an unconstrained motion-performed interaction with neither environment nor any other system, or constrained motion-system in contact with environment and/or other systems. This paper provides the function based design approach to formulate control of constrained system particularly bilateral systems in micromanipulation applications. The control objective aimed to maintain desired functional relations between human and environment defining convenient tasks and their proper relations on master and slave motion systems. Preliminary results concerning position tracking, force control and transparency between master and slave systems are clearly demonstrated.

Key words: Bilateral control, Motion control, Micromanipulation, Teleoperation

Bilateralno upravljanje zasnovano na zadacima za primjene u mikrosustavima. Sinteza slijednog sustava prikladnog za široki raspon primjena u industriji, svemiru, biologiji, medicini te posebno za primjene koje obuhvaćaju više raličitih fizikalnih okruženja, vrlo je važna. Dobro poznate strukture upravljanja poput slijeđenja trajektorije, usklađenog upravljanja i upravljanja interakcijskom silom predstavljaju znanstvene prekretnice koje imaju zajednički upravljački cilj: održavanje željene konfiguracije sustava. U ovom konceptu, slijedni sustav može biti sustav bez ograničenja i bez interakcije s okolinom ili ostalim sustavima, odnosno može biti sustav s ograničenjima koji je spregnut s okolinom i/ili drugim sustavima. Ovaj članak opisuje funkcijski zasnovanu sintezu sustava upravljanja za sustav s ograničenjima, a posebno za bilateralne sustave u mikromanipulacijskim primjenama. Cilj upravljanja je održavanje željenih funkcionalnih relacija izmežu čovjeka i okoline definirajući prikladne zadaće i njihove odgovarajuće relacije za glavni i podređeni slijedni sustav. Preliminarni rezultati vezani uz upravljanje pozicijom, upravljanje silom te veza između glavnog i podređenog sustava su jasno prezentirani.

Ključne riječi: bilateralno upravljanje, slijedni sustav, mikromanipulacija, teleoperacija

1 INTRODUCTION

Motion control systems are gaining importance as more and more sophisticated developments arise in technology. Technological improvements enhance incorporation of different research areas into the same framework. Trying to make systems function in different scaled environments (nano to macro) renders the design of control systems increasingly complex. In general, concepts of motion control systems can be categorized in different ways. Unconstrained motion, which has not any interaction with environment or other systems. Constrained motion in which system should modify its behavior due to interaction with environment or other systems like trajectory control or bilateral control. In remote operation control systems the sensation of unknown environment can be reflected to the human operator. In this study we would like to focus on function based control systems. It combines different concepts of motion control problems in the same framework while defining tasks. Tasks are real or virtual functions to realize the control objective. The possibility to enforce certain functional relations between coordinates of one or more motion systems represent a basis of the proposed algorithm. The core idea of the function based control is to design controller that enforces desired functional relation between system coordinates or between different systems. For example in bilateral system instead of controlling position and forces separately simple functional relation between master and slave is defined and controller maintains these functional relations while actual change of the coordinates is result of the dynamics of the master and slave systems. This way the functional interconnection of the systems is maintained despite the changes of the dynamics and motion of the individual systems. Application of such a control is very suitable for systems with human operator since operator may control the overall motion by interacting with only one of the systems and other systems would maintain desired functional relations. In this paper such a framework is applied to bilateral systems with human operator action on the master side and micro force manipulation on the slave side. It is demonstrated that motion control problems can be solved while defining motion by tasks which helps to decouple nonlinear dynamics and makes overall controller design simple [1]. The leading studies of function based control is proposed by by Tsuji, Nishi and Ohnishi in [2]. Arimoto and Nguyen in [3] investigated decentralized control with concepts such as linear superposition. The implementation of sliding mode control in bilateral systems is studied by Onal and Sabanovic in [4]. In this paper design of control for motion systems that should maintain defined functional relation among their coordinates will be discussed in the Sliding Mode Control (SMC) framework. As an example bilateral control systems, in which master and slave side must maintain relation, is demonostrated. Slave side tracks movement dictated by master side while transmitting accurately the sense of interaction force to master side system. Master and slave systems do not have mechanical interactions but they are related by fulfilling functional relation as described.

In literature numerous control algorithms are developed for bilateral systems. Some methods to obtain stability and total transparency of bilateral systems are presented as follows. Lawrences' papers [5] provide tools quantifying teleoperation system performance and stability when communication delays are presented. It is also shown that transparency and robust stability (passivity) are conflicting objectives, and a trade-off must be made in practical applications. The key to achieving the high levels of transparency is described. H. Zaad has showed the advantages of employing local force feedback for enhanced stability and performance in teleoperation systems [6]. In the presence of time-delays neither transparency nor stability is preserved and new control strategies have to be devised to resolve the problem, however, Katsura proved that whether or not there is time delay in the system, ideal transparency cannot be obtained [7]. Control with time delay issues is also addressed in [8] and [9]. In [10], Shimono, Katsura and Ohnishi offer a bilateral control algorithm for abstraction and reproduction of real world force sensation. Yokokohji and Yoshikawa discuss the analysis and design of master-slave teleoperation systems in order to build a superior master-slave system that can provide good maneuverability [11]. Sliding mode application to bilateral system is discussed in [12].

This paper is revived and extended version of the conference paper [13]. In this paper, function based control framework is defined and employed for bilateral system in micromanipulation applications. The remaining part of the paper is divided into five sections. The theoretical model of control and motion of systems and its extensions to general systems in interactions are presented in section II. Section III discusses function based control approach. In section IV, bilateral control systems are examined in function based control framework along with simulation results. Tele-micromanipulation setup is explained and preliminary results concerning the position/force tracking of master and slave are presented in section V. Finally, section VI gives the conclusion remarks.

2 PROBLEM FORMULATION

A mathematical description of system motion and control problem formulation [14] can be represented by,

$$\begin{array}{c} M(q)\ddot{q} + L(q,\dot{q})\dot{q} + H(q,\dot{q}) = F - F_{ext} \\ N(q,\dot{q}) = L(q,\dot{q})\dot{q} + H(q,\dot{q}) \end{array} \tag{1}$$

where $q \in \Re^n$ stands for vector of generalized positions, $\dot{q} \in \Re^n$ stands for vector of generalized velocities, $M(q) \in \Re^{n\times n}$, $M^- \le \|M(q)\| \le M^+$ is generalized positive definite inertia matrix with bounded parameters, $N(q,\dot{q}) \in \Re^{n\times 1}$, $\|N(q,\dot{q})\| \le N^+$ represent vector of coupling forces including gravity and friction, $F \in \Re^{n\times 1}$, $\|F\| \le F^+$ stands for vector of generalized input forces, $F_{ext} \in \Re^{n\times 1}$, $\|F_{ext}\| \le F_{0ext}$ stands for vector of external forces. M^-, M^+, N^+, F^+ and F_{0ext} are known scalars. The model (1) may be rewritten as n second order systems of the form,

$$m_{ii}\ddot{q}_i + n_i = F_i - F_{\text{ext},i} - \sum_{i=1,j\neq 1}^{n} m_{ij}\ddot{q}_j, i = 1,...,n \tag{2}$$

where elements of inertia matrix are bounded $m_{ij}^- \le \|m_{ij}(t)\| \le m_{ij}^+$, functions $n_i^- \le \|n_i(t)\| \le n_i^+$ are bounded, elements of the external force vector are bounded by $F_{0_i}^- \le \|F_{exti}(t)\| \le F_{0_i}^+$, and generalized input forces are bounded $F_i^- \le \|F_i(t)\| \le F_i^+$. External force, $F_{ext}(q_e, q)$ occurs if there is an interaction with environment.

2.1 Control Problem Formulation

Vector of generalized positions and generalized velocities defines configuration $\xi(q,\dot{q})$ of mechanical systems. The most general formulation of the fully actuated mechanical systems can be formulated as a task to maintain desired configuration $\xi^{ref}(q^{ref},\dot{q}^{ref})$ of the system.

$$\begin{array}{c} \sigma(\xi^{ref}(q^{ref},\dot{q}^{ref}) - \xi(q,\dot{q})) = 0_{n\times 1} \\ \sigma = 0_{n\times 1} \Rightarrow (\xi = \xi^{ref}) \end{array} \tag{3}$$

In this study, without loss of generality, it will be assumed that system configuration (3) can be expressed as a linear combination of generalized positions and velocities,

$$\begin{aligned} \xi(q,\dot{q}) &= Cq + Q\dot{q} \\ \xi^{ref} &= Cq^{ref} + Q\dot{q}^{ref} \end{aligned} \tag{4}$$

Now design can be formulated as a selection of the control so that the state of the system is forced to remain in manifold S_q:

$$\begin{gathered} S_q = \{q,\dot{q} : \sigma(\xi(q,\dot{q}),\xi^{ref}(q^{ref},\dot{q}^{ref})) \\ = \xi(q,\dot{q}) - \xi^{ref}(q^{ref},\dot{q}^{ref}) = 0\} \\ \sigma,\xi^{ref},\xi \in \Re^{n\times 1}; C,Q \in \Re^{n\times n}; C,Q > 0 \\ \sigma = [\sigma_1,\sigma_2,...,\sigma_n]^T \end{gathered} \tag{5}$$

where $\xi^{ref}(q,\dot{q}) \in \Re^{n\times 1}$ stands for reference configuration of the system and is assumed to be smooth bounded function with continuous first order time derivatives, matrices $C,Q \in \Re^{n\times n}$,$rank(C) = rank(Q) = n$. By selecting $C,Q \in \Re^{n\times n}$ as diagonal (5) can be represented by a set of n first order equations as (6)

$$\sigma_i = g_i(q_i^{ref} - q_i) + h_i(\dot{q}_i^{ref} - \dot{q}_i) = 0, i = 1,2,...,n \tag{6}$$

Design of control inputs for system (1) that will enforce the stability of $\sigma(\xi,\xi^{ref}) = 0_{n\times 1}$ and that manifold (5) is reached asymptotically or in finite time. The simplest and the most direct method to derive control is to enforce Lyapunov stability conditions for solution $\sigma(\xi,\xi^{ref}) = 0_{n\times 1}$ on the trajectories of system (1). As explained in [12] equations of motion and control input can be derived by considering sliding manifold as,

$$\sigma = Cq + Q\dot{q} - \xi^{ref} \tag{7}$$

The derivation of σ becomes,

$$\begin{aligned} \dot{\sigma} &= C\dot{q} + Q\ddot{q} - \dot{\xi}^{ref} \\ &= Q\{M^{-1}(F - N - F_{ext})\} + (C\dot{q} - \dot{\xi}^{ref}) \\ &= QM^{-1}\Big(F - \underbrace{(N + F_{ext} - (QM^{-1})^{-1}(C\dot{q} - \dot{\xi}^{ref}))}_{F_{eq}}\Big) \\ &= QM^{-1}(F - F_{eq}) \end{aligned} \tag{8}$$

By selecting Lyapunov candidate as $V = \sigma^T\sigma/2$ and requiring the control design so the stability requirement $\dot{V} = \sigma^T\dot{\sigma} = -\sigma^T\Psi(\sigma) \le 0$ is satisfied, one can find

$$\begin{aligned} \dot{\sigma} &+ \Psi(\sigma) = 0 \\ \dot{\sigma} &= -\Psi(\sigma) = QM^{-1}(F - F_{eq}) \\ F &= F_{eq} - ((QM)^{-1})^{-1}\Psi(\sigma) \end{aligned} \tag{9}$$

Where $\Psi(\sigma)$ can be linear or nonlinear or nonlinear single-valued function of σ satisfying $sign(\sigma) = sign(\Psi(\sigma))$ Equivalent control can be estimated as,

$$\dot{\sigma} = QM^{-1}(F - F_{eq}) \Longrightarrow \hat{F}_{eq} = W(s)\big(F - (QM^{-1})^{-1}s\sigma\big) \tag{10}$$

Where $W(s)$ is an appropriate filter such that,

$$\hat{F}_{eq} = F_{eq}W(s)_{s\to 0} \Longrightarrow F_{eq} \tag{11}$$

$$F = \hat{F}_{eq} - (QM^{-1})^{-1}\psi(\sigma) \tag{12}$$

The error introduced by such estimation is,

$$\dot{\sigma} + \Psi(\sigma) = F - \hat{F}_{eq} = 1 - W(s) \tag{13}$$

The above equation is small if $W(s) \approx 1$. By inserting (8) into (1) equations of motion in manifold (3) may be written as,

$$\begin{gathered} M\ddot{q} = (QM^{-1})^{-1}[(\dot{\xi}^{ref} - C\dot{q}) - \psi(\sigma)] \\ M\ddot{q}^{des} = M\ddot{q} \end{gathered} \tag{14}$$

Since $Q \in \Re^{n\times n}$ and $M \in \Re^{n\times n}$ are full rank matrices then $(QM^{-1})^{-1} = MQ^{-1}$ and (6) can be rewritten as

$$\begin{gathered} \ddot{q}^{des} = Q^{-1}[(\xi^{ref} - C\dot{q})\psi(\sigma)] \\ \ddot{q} = \ddot{q}^{des} \end{gathered} \tag{15}$$

Motion (15) of the system (1) under control (12) depends on selection of the manifold (5) and the reference configuration $\xi^{ref} \in \Re^{n\times 1}$. [12] shows that closed loop system realizes an acceleration controller with desired acceleration.

3 FUNCTION BASED CONTROL

Complexity of controller design is one of the problems for motion control systems applications in human environment. Human environment has many variables so that robots need to execute multiple actions in parallel. The idea of functionality comes as a mean to express these actions as the tasks describing the separate roles of the system. [2], [15], [16] define the system role as a function of the system coordinates. Such an approach allows mapping of the system dynamics into a new set of coordinates in situation when the resulting system can be made diagonal; design of the control for each role-function separately, and then transform selected control back to the original system space. In the proposed work the mapping to the role-function space has been done with constant elements of the matrix that describe mapping. Additionally mapping matrix was selected to be regular since the inverse of the same matrix has been used to map control actions back to the original system space. The idea of the role-function is extended to the general formulation in which the overall role of the system is presented as a vector with dimension equal to the dimension of the control vector and it's components are continuous linear or nonlinear single valued functions of the generalized system coordinates. Such a formulation allows more general treatment of the role-function in the context of the systems tasks and at the same time it is very suitable for the application of the sliding mode design methods. Since the role-function space is of the same dimension as the control input which allows the decomposition of the system in such a way that control for each role-function is selected independently and then fused back to the original system via appropriate mapping. In this paper the problems where the dimension of the role-function space is not equal to the dimension of the control vector is not treated but it is very interesting for evaluation.

In the situation depicted above, motion control systems maintain desired functional relation (for example bilateral control or cooperating robots etc.). In such systems, control should be selected to maintain a functional relation by acting on all of the subsystems. In bilateral control architecture, assume a set of n single dof motion systems each can represented by (16) or in the vector form as (17)

$$S_i : m_i(q_i)\ddot{q}_i + n_i(q_i, \dot{q}_i, t) = f_i - f_{iext}, \quad i = 1, 2, ..., n \tag{16}$$

$$S : M(q)\ddot{q} + N(q, \dot{q}, t) = BF - d_\Sigma \tag{17}$$

$q \in \Re^{n\times1}$, $rank(B) = rank(M) = n$, vectors N, d_Σ satisfy matching conditions. Assume also that required role $\Phi \in \Re$ of the system S may be represented as a set of smooth linearly independent functions $\zeta_1(q), \zeta_2(q), ..., \zeta_n(q)$ and role vector can be defined as $\Phi^T = [\zeta_1(q)...\zeta_n(q)]$. Consider problem of designing control for system (9) such that role vector $\Phi \in \Re^{n\times1}$ tracks its smooth reference $\Phi^{ref} \in \Re^{n\times1}$.

This part of study defines function based control framework for constrained motion systems. Let sliding mode manifold $\sigma_\phi \in \Re^{n\times1}$ be defined as

$$S_\phi = \{(q, \dot{q}) : \xi_\phi^{ref}(\phi^{ref}, \dot{\phi}^{ref}) - \xi_\phi(\phi, \dot{\phi}) = \sigma_\phi, \sigma_\phi = 0\} \tag{18}$$

By calculating $\dot{\phi} = [\frac{\partial\phi}{\partial q}]\dot{q} = J_\phi\dot{q}$ with $J_\phi = [\frac{\partial\phi}{\partial q}]$, one can determine $\ddot{\phi} = \hat{B}F + \hat{d}_\Sigma$ where $\hat{B} = J_\phi M^{-1}B$ and $\hat{d}_\Sigma = J_\phi M^{-1}(-N(q, \dot{q}, t) - d_\Sigma) + \dot{J}_\phi\dot{q}$. By introducing $[\frac{\partial\xi_\phi}{\partial\dot{\phi}}] = Q_\phi$ and $[\frac{\partial\xi_\phi}{\partial\phi}] = C_\phi$ projection of the system motion on manifold S_ϕ, can be expressed as $\frac{d\sigma_\phi}{dt} = Q_\phi\hat{B}F + (\hat{d}_\Sigma + C_\phi\dot{\phi} - \dot{\xi}_\phi^{ref})$. With $\hat{d}_\phi = \hat{d}_\Sigma + C_\phi\dot{\phi} - \dot{\xi}_\phi^{ref}$ and $F_\phi = Q_\phi\hat{B}F$, it can be simplified as $\dot{\sigma}_{\phi_i} = F_{\phi_i} + \hat{d}_{\phi_i}$, $i = 1, ..., n$ for which design of control F_{ϕ_i} is straightforward. If $(Q_\phi\hat{B})^{-1} = (Q_\phi J_\phi M^{-1}B)^{-1}$ exists then inverse transformation $F = (Q_\phi\hat{B})^{-1}F_\phi$ gives control in the original state space. Since $M \in \Re^{n\times n}$ and $B \in \Re^{n\times n}$ are square full rank matrices then one can determine conditions that matrices J_ϕ and Q_ϕ should satisfy in order that $(Q_\phi J_\phi M^{-1}B)$ exists. Since $Q_\phi, J_\phi, M, B \in \Re^{n\times n}$ sufficient conditions for having unique solutions or control F is $rank(Q_\phi J_\phi) = n$.

4 BILATERAL CONTROL

Researchers have studied bilateral systems for a long time, however, in recent decades; the ability that is required from these systems has changed and they have become indispensable part of microsystems handling tasks, required to pass force sensation and position information of micro world to the macro world. In this section the design of the bilateral system will be presented in the framework described in the previous section. Our aim is to design mechatronics interface for the manipulation of the micron size objects under visual microscope using available force feedback from the microsystem - slave side. Both the master and the slave system are treated as the single DOF systems.

Assume the dynamic model of master and slave system as:

$$m_i\ddot{x}_i - d_i = F_i - F_{iext}, i = m, s \tag{19}$$

where masses $m_i; i = m, s$ are assumed known and the disturbances $d_i; i = m, s$ are assumed unknown bounded functions of time and/or of the system coordinates. In bilateral control a specific functional relation between master and slave systems is established. That functional relation is defined as,

$$\begin{aligned} x_s &= x_m \\ F_m &= -F_s \end{aligned} \tag{20}$$

Behavior of ideal bilateral system is defined as requirement that error in position (21) and the error in force (22) are zero.

$$\varepsilon_x(t) = x_{m(t)} - x_{s(t)} \tag{21}$$

$$\varepsilon_F(t) = F_{sext(t)} + F_{mext(t)} \tag{22}$$

There are many possible ways to approach design of control on master and slave side. In control system design, for single dof identical master and slave systems, is performed applying disturbance feedback [17] so that master and slave subsystems are represented as $\ddot{x}_i = F_i, i = m, s$ and then the acceleration controller can be designed for plants as $\ddot{\varepsilon}_x = \ddot{x}_m - \ddot{x}_s = F_{mext} - F_{sext} = F_x$ and $\ddot{\varepsilon}_F = \ddot{x}_m + \ddot{x}_s = F_{mext} + F_{sext} = F_F$. Now selection of F_x and F_F is a simple task and the real control inputs are easily obtained [12] as $F_m = \frac{1}{2}(F_x + F_F), F_s = \frac{1}{2}(F_F - F_x)$. In this approach the design is performed in very similar way as standard SMC is done. Namely the original plant is projected in the new subspace in which the control inputs are selected and then control is projected back to the original state space. The result can be extended to microsystems with scaling between master and slave side and to multilateral control [18].

In the above equations the system requirements are defined in term of the acceleration. Such a formulation requires compensation of the system disturbance in the joint space so that the compensated system can be presented as double integrator systems. In such case the force and acceleration are related just by a constant term thus the formulation of the system requirements in term of acceleration or in term of forces is equivalent. In uncompensated system proposed formulation may have some difficulties due to the fact that parameters variation, the operator and the environment impedances along with the disturbance will be entering into the play. In addition in the above formulation the operators impedance is not taken into account. In this paper the controller design will be discussed in the interaction of function based and sliding mode control frameworks. In such systems the first step in design is to select sliding mode manifolds on which the motion of the system will be constrained. In bilateral control system, consisting of functionally related master and slave subsystems as defined by (21) and (22) the selection of the force tracking manifold should be defined taking into consideration the impedance of the human operator as depicted in (23). Force tracking manifold is selected as a difference between force perceived by operator defined by spring C_h and damper D_h coefficients and the force appearing in the interaction with environment defined by spring C_e and damper D_e coefficients. The environment impedance may not be known so in (23) just the slave side force can be used instead. The selection of the position tracking manifold is straight forward and is defined as in (24).

$$\begin{aligned} f_h &= C_h x_m + D_h \dot{x}_m \\ f_s &= f_e = C_e x_s + D_e \dot{x}_s \\ S_F &= \{x_m, x_s : \sigma_F = f_h + f_s = 0\} \\ \sigma_F &= C_h x_m + D_h \dot{x}_m + C_e x_s + D_e \dot{x}_s \end{aligned} \tag{23}$$

$$S_x = \{(x_m, x_s) : Q\dot{\varepsilon}_x + G_x \varepsilon_x = \sigma_x = 0\} \tag{24}$$

In the above formulation the coefficients C_h and D_h can be selected in such a way that impedance perceived by the human operator is shaped in order to give a feeling of a virtual tool in operator's hand. Impedance shaping gains importance particularly for cases in which characteristic impedance of the task and the operator are very different from each other. That case is usual in micromanipulation where forces in the micro scale are different from the operator perception. Due to the fact that the human impedance needs to be adjusted and that the impedance of environment may not be known (and generally is not) the force tracking manifold (23) can be rewritten in the following form

$$\begin{aligned} S_F &= \{x_m, x_s : \sigma_F = f_h + f_s\} \\ \sigma_F &= D_h(\dot{x}_m + \dot{x}_s) + C_h(x_m + x_s) \\ &\quad + (C_e - C_h)x_s + (D_e - D_h)\dot{x}_s \\ &= D_h \dot{\varepsilon}_F + C_h \varepsilon_F + (C_e - C_h)x_s \\ &\quad + (D_e - D_h)\dot{x}_s \\ \varepsilon_F &= x_m + x_s \end{aligned} \tag{25}$$

$$\zeta(x_s, \dot{x}_s) = (C_e - C_h)x_s + (D_e - D_h)\dot{x}_s \tag{26}$$

With such selection of the sliding functional relations between master and slave systems the application of the sliding mode framework is a straight forward task. Bilateral system functional relationship is achieved if sliding mode is enforced on the intersection of the above manifolds [17]:

$$S_B = \{(x_m, \dot{x}_m, x_s, \dot{x}_s) : S_x \cap S_F, \sigma_x \cap \sigma_F = 0\} \tag{27}$$

Now projection of the system motion in the selected manifolds can be expressed as

$$\dot{\sigma}_x = Q\ddot{\varepsilon}_x + G_x \dot{\varepsilon}_x \tag{28}$$

$$\dot{\sigma}_x = Q_x\left[\left(\tfrac{1}{m_m}F_m + \tfrac{1}{m_s}F_s\right) - \left(\tfrac{1}{m_m}d_m - \tfrac{1}{m_s}d_s\right)\right] + G_x \dot{\varepsilon}_x \tag{29}$$

$$\begin{aligned} \dot{\sigma}_F &= D_h \ddot{\varepsilon}_F + C_h \dot{\varepsilon}_F + (C_e - C_h)\dot{x}_s + (D_e - D_h)\ddot{x}_s \\ &= D_h \ddot{\varepsilon}_F + \xi(\varepsilon_F, x_s) \\ \xi(\varepsilon_F, x_s) &= C_h \dot{\varepsilon}_F + (C_e - C_h)\dot{x}_s + (D_e - D_h)\ddot{x}_s \end{aligned} \tag{30}$$

$$\dot{\sigma}_F = D_h\left(\frac{F_m}{m_m} + \frac{F_s}{m_s}\right) + D_h\left(\frac{d_m}{m_m} + \frac{d_s}{m_s}\right) + \xi(\varepsilon_F, x_s) \tag{31}$$

Equations (29) and (31) represent simple first order systems with control being linear combination of the master and the slave control inputs. They can be rewritten in the form:

$$\dot{\sigma}_x = F_x + d_x \tag{32}$$

$$\dot{\sigma}_F = F_F + d_F \tag{33}$$

The selection of the controller for (32) and (33) like in (12) will satisfy the stability conditions and ensure that the sliding mode is enforced in intersection (27) thus ensuring the motion of the system in intersection of manifolds (23) and (24). That way the condition for the bilateral systems operation (21) and (22) are satisfied. In such a design both impedance of environment and the desired impedance on the operator's side are taken into account due to the enforcement of the sliding mode. The controller may be designed also by applying simple disturbance observer with a first order filter as,

$$\hat{d}_i = -g\sigma_i + (F_i - g\sigma_i)g/(s+g); i = x, F \tag{34}$$

Along with simple proportional controller to obtain $F_x = -\hat{d}_x - k_x\sigma_x, k_x > 0$ and $F_F = -\hat{d}_F - k_F\sigma_F, k_F > 0$. Then the changes in the control errors may be expressed as $\dot{\sigma}_x + k_x\sigma_x = d_x - \hat{d}_x \approx 0$ and $\dot{\sigma}_F + k_F\sigma_F = d_F - \hat{d}_F \approx 0$ thus both are converging to zero and have asymptotically stable zero solution. In this case asymptotic stability of the motion towards manifold is ensured and thus asymptotic stability of the (21) and (22). Both methods are satisfying at least exponential stability conditions. The difference is in the fact that sliding mode guaranty finite time convergence thus the conditions (21) and (22) will be satisfied exactly for $t > t_0$ where t_0 is so-called reaching time.

The relationship between master and the slave controlled to fulfill interaction may be defined by relation of positions and forces of the two systems. The relation in general may be represented as a structure with four variables the position and force on the master and on the slave side. In [19] that relation is formulated using hybrid matrix as,

$$\begin{bmatrix} f_m \\ x_m \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} x_s \\ -f_s \end{bmatrix} \tag{35}$$

Taking into account that $f_s = Z_e x_s$, where Z_e stands for the environment impedance, the master side force can be expressed as $f_m = (h_{11} - h_{12}Z_e)(h_{21} - h_{22}Z_e)^{-1}x_m$. The indices of "reproducibility" $P_r = -h_{12}(h_{21} - h_{22}Z_e)^{-1}$ and "operationality" $P_o = h_{11}(h_{21} - h_{22}Z_e)^{-1}$ have been used [20] to quantify the operation of a bilateral system. The closeness of "reproducibility" to one means good reproduction of the impedance of environment on the master side. The "operationality" shows uncompensated additional force in the system due to not full compensation of the interactions in the system. For solution discussed in this section the parameters of H matrix can be determined from the $\dot{\sigma_x} + k_x\sigma_x = d_x - \hat{d}_x = p_x$ and $\dot{\sigma_F} + k_F\sigma_F = d_F - \hat{d}_F = p_F$ as

$$\begin{bmatrix} f_h \\ x_m \end{bmatrix} = \begin{bmatrix} \frac{p_F}{Z_F} & 1 \\ 1 & \frac{p_x}{Z_x} \end{bmatrix} \begin{bmatrix} x_s \\ -f_s \end{bmatrix} \tag{36}$$

Where,

$$\begin{aligned} Z_x &= Q_x s^2 + (G_x + k_x Q_x)s + k_x G_x \\ Z_F &= D_h s^2 + (C_h + k_F D_h)s + k_F C_h \\ p_x &= d_x - \hat{d}_x \\ p_F &= d_F - \hat{d}_F \end{aligned} \tag{37}$$

The "reproducibility" and "operationality" may be expressed as,

$$\begin{aligned} P_r &= -\frac{H_{12}}{H_{21} - H_{22}Z_e} = \frac{1}{1 - \frac{p_x}{Z_x}Z_e} = \\ &= \frac{Z_x}{Z_x - p_x Z_e} \lim_{p_x \to 0} \to 1 \\ P_o &= \frac{H_{11}}{H_{21} - H_{22}Z_e} = \frac{\frac{p_F}{Z_F}}{1 - \frac{p_x}{Z_x}Z_e} = \\ &= \frac{Z_{xf}}{Z_F} \frac{p_F}{Z_x - p_x Z_e} \lim_{p_F \to 0} \to 0 \end{aligned} \tag{38}$$

The "operationality" can be controlled by the disturbance compensation on master and slave side thus it essentially depends on the disturbance observer. The reproducibility depends on the compensation of the disturbance in the force control channel. The "reproducibility"" may be improved by careful design of the disturbance observer in the force control loop and by selecting force controller that has high gain in the range of frequencies of interest. The ideal operation is obtained if $H_{11} = H_{22} = 0$ and $H_{12} = -1, H_{21} = 1$. By finding ration x_m/x_s, and $f_h/(-f_s)$ from closed loop behavior of the system $\dot{\sigma}_x + k_x\sigma_x = 0$ and $\dot{\sigma}_F + k_F\sigma_F = 0$ one can find that proposed system asymptotically tends to the ideal bilateral system. The asymptotic convergence of the hybrid parameters to the theoretical values is the most salient difference of this approach as compared with other results [18], [21] in bilateral control.

4.1 Simulation Results

In this simulation the effectiveness of the proposed control structure is investigated in the setting when master and slave are single degrees of freedom (DOF) systems. Operator driven input force is generated on master side to execute desired motion. The slave side, moving free or in contact with environment, is required to track master's position as directed by operator. On the other hand, interaction force with environment on the slave side is to be transferred to the master as a force opposing its motion, therefore causing a "feeling" of the environment by the operator. Master robot has 10 μm initial position and human generates the current input for the master motion. In order to generate interaction force due to movement of the slave in the environment, a sinusoidal obstacle is defined with amplitude: 0.0002, frequency: 2pi/11 and phase: pi/2. The slave robot tracks the master robot position directed by the human operator in presence of obstacle location along with the position tracking error is shown in [13]. It is demonstrated that position control is achieved while $\varepsilon_x \to 0$. Besides, band-limited white noise with 10^{-20} noise power is given to both the master and the slave robots as illustrated in Figure 1. Master manipulator should give the sense of force to human operator. Figure 2 shows the force response along with the error [13] response while $\varepsilon_F \rightarrow 0$. Spring and damper coefficients to model operator and environment are $C_e = C_h = 150$, $D_e = D_h = 2$; PID controllers are used with disturbance observer, the controller and observer parameters are $P = 25$, $D = 15$, $g = 500Hz$. Since impedance values used to model human and environment are the same, magnitudes of forces on master and slave manipulators are the same. Position tracking performance and force transparency are satisfactory.

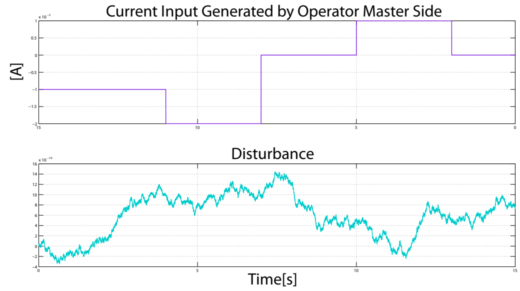

Fig. 1. Disturbances acting on the master and the slave

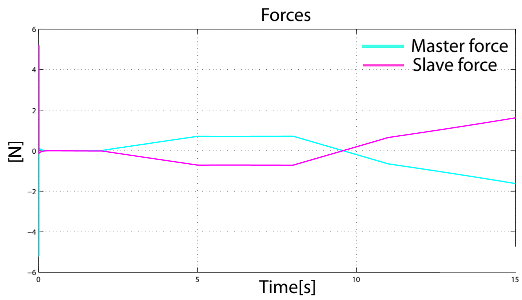

Fig. 2. Force tracking between the master and the slave

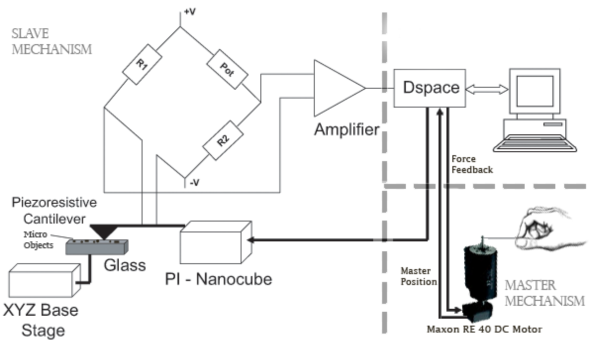

Fig. 3. Schematic tele-micromanipulation setup

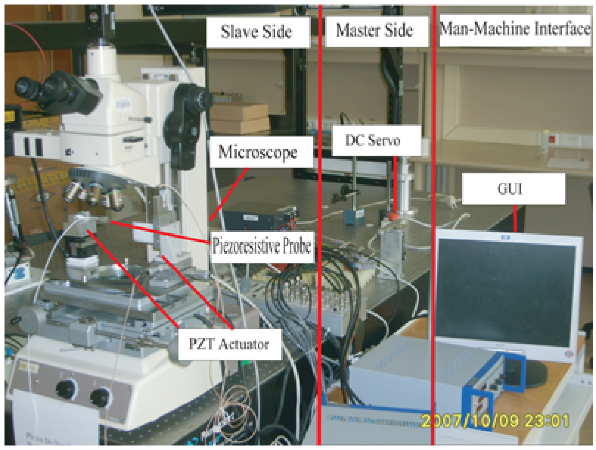

Fig. 4. Experimental setup of tele-Micromanipulation

5 TELE-MICROMANIPULATION

In order to investigate the above mentioned function based bilateral structure, a custom built tele-micromanipulation setup has been developed on which the implementation of bilateral structure is being pursued. The schematic and description of the experimental setup [22] is depicted in Figure 3, and Figure 4 respectively.

The system is composed of three parts, namely a master mechanism operated by the human operator, a slave mechanism interacting with the micro environment and a man-machine interface. For the master mechanism a DC motor is utilized, while a piezoresistive microprobe attached on PZT stacks is used for the slave. The position data from the master side is scaled and transferred to slave side, while simultaneously, the force measured at the slave side is scaled and transferred back to master. A graphical display is also made available to the operator. The one degree of freedom master mechanism consists of a brushed DC servo (Maxon motors RE40) and is manually excited with the help of a light rod that is connected to the shaft. The slave mechanism includes different components to ensure reliable and efficient micromanipulation. Capability to control positions with nanometer accuracy and to estimate the forces in nano-Newton scales is required. High magnification microscopy is also essential for visual feedback with acceptable resolution.

An open architecture micromanipulation system that satisfies the requirements has been developed and used as the slave mechanism. Nano scale positioning [23] of the micro-cantilever has been provided using three axes piezo stages (P-611 by Physik Instrumente) which are driven by a power amplifier (E-664) in closed loop external control mode. Potentiometers (strain gauge sensors) integrated in the amplifier, are utilized for position measurement of the closed loop stages which possess a travel range of $100\mu m$

per axis with one nanometer theoretical resolution. Sticционless and frictionless compliant guiding systems exist in the stages. An open loop piezoelectric micrometer drive (PiezoMike PI-854 from Physik Instrumente) has been utilized as the base stage, which is equipped with integrated high resolution piezo linear drives [24]. Manually operable linear drives are capable of $1\mu m$ resolution and the automatic movement range of the micrometer tip with respect to the position can be set $50\mu m$ ($25\mu m$ in/out). Nanometer range resolution is achieved for this movement by controlling the piezo voltage [25]. As for the force feedback, a piezoresistive AFM cantilever has been utilized along with a custom built Wheatstone bridge as discussed in the next subsection. A real time capable control card (dSPACE DS1103) is used as control platform and an optical microscope (Nikon MM-40) is used for visual feedback.

5.1 Force Sensing in Nano-Newton Range

In order to achieve transparency between the master and the slave device, it is necessary to sense the interaction forces between the slave device and the environment with high accuracies and high bandwidth [21], [20]. A commercially available piezoresistive microcantilever from AppliedNanostructures with an integrated lightly-doped strain gauge is utilized as the force sensor. As the force is applied at the free end of the cantilever, the change of resistance takes place depending on deflection. The amount of deflection is measured by a Wheatstone bridge which provides a voltage output, which is amplified by the amplifier. To match with the initial cantilever resistance value, one of the active resistors in the full bridge is replaced by a potentiometer. The amplified voltage is sent to the data acquisition card, and the force is calculated using Hooke's law,

$$F = K_c\, z \tag{39}$$

where K_c is the known spring constant of $0.3603\,N/m$ and z is the amount of cantilever deflection. The spring constant is calculated by considering a linear beam equation and is represented as,

$$K = \frac{3\,E\,I}{L^3} \tag{40}$$

where E represents modulus of elasticity (190 GPa for silicon)and I represent the moment of inertia calculated as

$$I = \frac{b\,h^3}{12} \tag{41}$$

where b and h represents the width and height of the microcantilever which is 50 microns and 1.6 microns respectively and the calculated value of moment of inertia is $17.067 \times 10^{-24}\, m^4$. The cantilever is mounted on the three axes closed loop stage and the x-axis is moved so that cantilever tip comes in contact with the glass slide which is supported by three axes open loop PZT actuators. The interaction (contact and non-contact) forces between the tip and glass slide are measured. The force measurement data is shown in Figure 5. The movement of the cantilever is selected to be perpendicular to the plane of the optical axis in order to achieve better visibility of the distance between the cantilever and the glass slide. Since the displacement range of the x-axis of the closed loop stage is 100 μm, the glass slide is brought within the range using open-loop manual PZT axes. Finally the change of the resistance is converted to change in voltage (millivolt range) using the full bridge, which in turn is converted to $\mp 10V$ range using the amplifier.

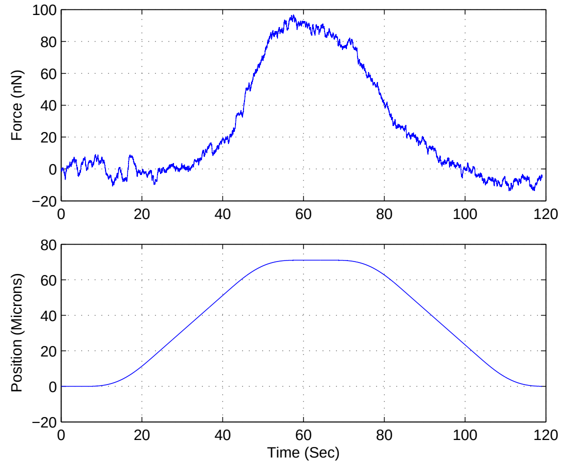

Fig. 5. Forces during pulling in-out for smooth step position references

Figure 5 represents the attractive forces for pulling in and in-out phase respectively between the tip and glass slide.The decreasing distance between the tip and glass slides is represented by the increase in the position of PZT axis. As the distance between the tip and glass slide decreases the attractive forces increases and vice-versa.

5.2 Experimental Validation of Bilateral Control

The overall structure of bilateral control utilized in telemicromanipulation is depicted in Figure 6 [26].

Piezo stage on the slave side is position controlled to track master's position as dictated by the operator. The one dimensional interaction force with the environment, measured by the piezoresistive cantilever, is transferred to the master side and is reflected to the operator rendering a "feel" of the environment. To be able to meaningfully interact with the micro environment, positions and forces are scaled to match the operator requirements. In the first and second experiments, scaling factors of $\alpha = 0.027\ \mu$ m/deg and $\beta = 0.00366$ N/nN are used, that is an angular

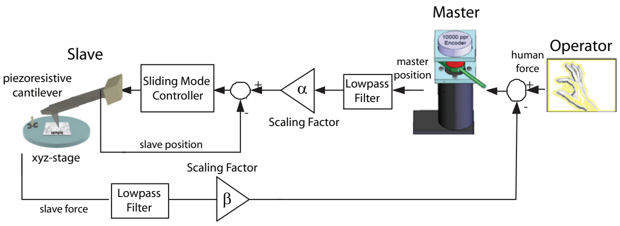

Fig. 6. Bilateral control structure

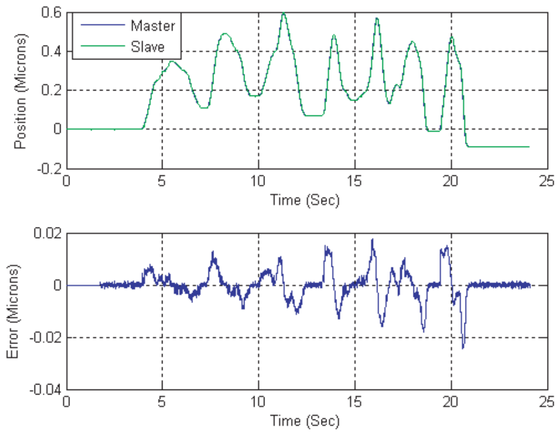

Fig. 7. Position tracking and error between the master and the slave

displacement of 1 deg on the master side corresponds to a linear displacement of 1 μm on the slave side and a force of 0.00366 nN on the slave side corresponds to a force of 1 N on the master side. In order to eliminate oscillations due to hand tremor of the operator and unmodelled dynamics of the piezoresistive cantilever, position measured at the master side and force measured at the slave side are low pass filtered with 10 KHz before scaling.

Figure 7 illustrates the experimental results for position tracking of the bilateral controller. Tracking error between master and slave systems is also presented. For slow motions of the slave with $0.6 \times 10^{-6} m$ amplitude, the tracking error ranges between $0.02 \times 10^{-6} m$. This position tracking performance is acceptable for properly positioning the micro cantilever for pushing. Due to the very slow motion of the master and slave sides the force is only due to the spring action and is just proportional to the position error.

Figure 8 demonstrates the force tracking between the master and slave along with the tracking error. It can be clearly observed from the figures that the master tracks the slave force precisely. Force tracking also confirms the transparency between the master and the slave.

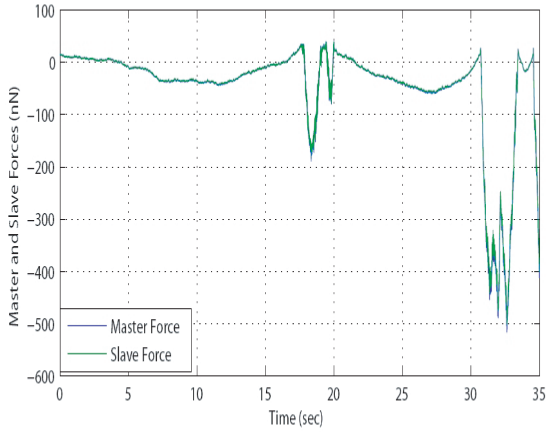

Fig. 8. Force tracking between the master and the slave

6 CONCLUSION

In the present paper, we proposed that function based control can be used in controlling systems in interactions by establishing desired functional relations between systems. It has been shown that the behavior of bilateral systems combining macro and micro scales can be modeled and controlled using function based control. In this framework, bilateral control tasks can be formulated as a requirement to enforce stability on the intersection of the position tracking and force tracking manifolds in the state space of the system. Furthermore, position and force control performances of the bilateral system are demonstrated via simulation results. A custom built micromanipulation setup along with scaled bilateral control architecture is utilized. Disturbance observer based on discrete sliding mode controller is employed. Both position and force control results are presented using the setup. Simulation and experimental results encouraged that function based control approach can be applied to the bilateral control of micromanipulation systems. The present approach can be extended to the problems where the dimension of the role function is not equal to the dimension of the control vector.

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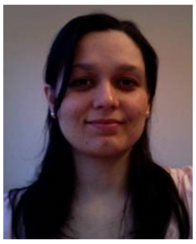

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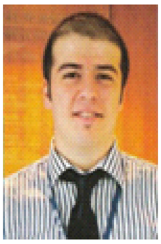

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