Function Based Control for Bilateral Systems in Tele-Micromanipulation

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***Abstract*— Design of a motion control system should take into account (a) unconstrained motion performed without interaction with environment or any other system, and (b) constrained motion with system in contact with environment or other systems. Control in both cases can be formulated in terms of maintaining desired system configuration what makes essentially the same structure for common tasks: trajectory tracking, interaction force control, compliance control etc. The same design approach can be used to formulate control in bilateral systems aimed to maintain desired functional relations between human and environment through master and slave motion systems. Implementation of the methodology is currently being pursued with a custom built Tele-micromanipulation setup and preliminary results concerning force/position tracking and transparency between master and slave are clearly demonstrated.**

I. 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 while trying to make systems function in unstructured environments renders the design of control systems increasingly complex. In general design of motion control system should take into account (i) unconstrained motion - performed without interaction with environment or other systems (ii) motion in which system should maintain its trajectory despite of the interaction with other systems (iii) constrained motion where system should modify its behavior due to interaction with environment or another system or should maintain specified interconnection - virtual or real - with other systems and (iv) in remote operation control systems should be able to reflect the sensation of unknown environment to the human operator.Decentralized control as a family of function based control systems seems a promising framework for applications in motion control systems with concepts such as linear superposition as shown by Arimoto and Nguyen in [1], or function based control proposed by Tsuji, Nishi and Ohnishi in [9], the implementation of sliding mode control in bilateral systems as proposed by Onal and Sabanovic in [3] to name some of the ideas.

In this work, function based control design is proposed to control motion systems in interaction, which considers bilateral control systems as an example. The possibility to enforce certain functional relations between coordinates of one or more motion systems represent a basis of the proposed algorithm. It is demonstrated that motion control problems can be solved while defining motion by tasks which helps to decouple the nonlinear dynamics and makes overall controller design simple.

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 [4] 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 [5]. 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 [6]. 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 [7]. Sliding mode application to bilateral system is discussed in [8].

The study begins in section II with mathematical formulations of control and motion of systems and its extension to general systems in interactions. The following section discusses function based control approach. In section III, 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 IV. Finally, section V concludes the study.

II. Problem Formulation

For fully actuated mechanical systems mathematical model may be found in the following form [10].

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

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where $q \in \Re^n$ stands for vector of generalized positions, $\dot{q} \in \Re^n$ stands for vector of generalized velocities, $M(q) \in \Re^{nxn}$, $M^- \leq \|M(q)\| \leq M^+$ is generalized positive definite inertia matrix with bounded parameters, $N(q, \dot{q}) \in \Re^{nx1}$, $\|N(q, \dot{q})\| \leq N^+$ represent vector of coupling forces including gravity and friction, $F \in \Re^{nx1}$, $\|F\| \leq F^+$ stands for vector of generalized input forces, $F_{ext} \in \Re^{nx1}$, $\|F_{ext}\| \leq F_{0ext}$ 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 $m_{ii}\ddot{q}_i + n_i = F_i - Fext_i - \sum_{i=1,j\neq 1}^{n} m_{ij}\ddot{q}_j$, $i = 1, ..., n$ where elements of inertia matrix are bounded $m_{ij}^- \leq \|m_{ij}(t)\| \leq m_{ij}^+$, functions $n_i^- \leq \|n_i(t)\| \leq n_i^+$ are bounded, elements of the external force vector are bounded by $F_{0i}^- \leq \|F_ext_i(t)\| \leq F_{0i}^+$, and generalized input forces are bounded $F_i^- \leq \|F_i(t)\| \leq F_i^+$. External force, $F_{ext}(q_e, q)$ occurs if there is an interaction with environment.

A. 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.

$$\begin{gathered}\sigma(\xi^{ref}(q^{ref}, \dot{q}^{ref}), \xi(q, \dot{q})) = 0_{nx1} \\ \sigma = 0_{nx1} \Rightarrow (\xi = \xi^{ref})\end{gathered} \tag{2}$$

In this study, without loss of generality, it will be assumed that system configuration (1) can be expressed as a linear combination of generalized positions and velocities $\xi(q, \dot{q}) = Cq + Q\dot{q}$ and $\xi^{ref} = Cq^{ref} + Q\dot{q}^{ref}$. Now control problem can be formulated as a selection of the control so that the state of the system is forced to remain in manifold S_q:

$$\begin{gathered}S_q = \{q, \dot{q} : \sigma(\xi(q, \dot{q}), \xi^{ref}(q^{ref}, \dot{q}^{ref})) \\ = \xi(q, \dot{q}) - \xi^{ref}(q^{ref}, \dot{q}^{ref}) = 0\} \\ \sigma, \xi^{ref}, \xi \in \Re^{nx1}; C, Q \in \Re^{nxn}; C, Q > 0 \\ \sigma = [\sigma_1, \sigma_2, ..., \sigma_n]^T\end{gathered} \tag{3}$$

where $\xi^{ref}(q, \dot{q}) \in \Re^{nx1}$ stands for reference configuration of the system and is assumed to be smooth bounded function with continuous first order time derivatives, matrices $C, Q \in \Re^{nxn}$,$rank(C) = rank(Q) = n$. By selecting $C, Q \in \Re^{nxn}$ as diagonal (3) can be represented by a set of n first order equations as (4)

$$\sigma_i = g_i(q_i^{ref} - q_i) + h_i(\dot{q}_i^{ref} - \dot{q}_i) = 0, i = 1, 2, ..., n \tag{4}$$

Design of control inputs for system (1) that will enforce the stability of $\sigma(\xi, \xi^{ref}) = 0_{nx1}$ and that manifold (3) 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 $\sigma(\xi, \xi^{ref}) = 0_{nx1}$ on the trajectories of system (1). As explained in [8] control input, equations of motion were derived as follows

$$F = F_{eq} - (QM^{-1})^{-1}\psi(\sigma) \tag{5}$$

$$\begin{gathered}M\ddot{q} = (QM^{-1})^{-1}[(\dot{\xi}^{ref} - C\dot{q}) - \psi(\sigma)] \\ M\ddot{q}^{des} = M\ddot{q}\end{gathered} \tag{6}$$

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

$$\begin{gathered}\ddot{q}^{des} = Q^{-1}[(\xi^{ref} - C\dot{q})\psi(\sigma)] \\ \ddot{q} = \ddot{q}^{des}\end{gathered} \tag{7}$$

Motion (7) of the system (1) under control (5) depends on selection of the manifold (3) and the reference configuration $\xi^{ref} \in \Re^{nx1}$. [8] shows that closed loop system realizes an acceleration controller with desired acceleration.

III. Function Based Control

Complexity of controller design is one of the problems for motion control systems application 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. In [9],[10],[11] Tsuji, Onhisi and Nishi 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; 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. In this work 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 itc components are continuous linear or nonlinear single valued functions of the system generalized coordinates. This 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 what 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 that problem 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 (8) or in the vector form as (9)

$$S_i : m_i(q_i)\ddot{q}_i + n_i(q_i, \dot{q}_i, t) = f_i - f_{iext}, i = 1, 2, ..., n \quad (8)$$

$$S : M(q)\ddot{q} + N(q, \dot{q}, t) = BF - d_\Sigma \quad (9)$$

$q \in \Re^{nx1}$, $rankB = rankM = n$, 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 $\Phi \in \Re^{nx1}$ tracks its smooth reference $\Phi^{ref} \in \Re^{nx1}$.

This part of study defines function based control framework for constrained motion systems. Let sliding mode manifold $\sigma_\phi \in \Re^{nx1}$ be defined as

$$S_\phi = \{(q, \dot{q}) : \xi_\phi^{ref}(\phi^{ref}, \dot{\phi}^{ref}) - \xi_\phi(\phi, \dot{\phi}) = \sigma_\phi, \sigma_\phi = 0\} \quad (10)$$

By calculating $\dot{\phi} = \left[\frac{\partial \phi}{\partial q}\right]\dot{q} = J_\phi \dot{q}$ with $J_\phi = \left[\frac{\partial \phi}{\partial q}\right]$, 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 $\left[\frac{\partial \xi_\phi}{\partial \dot{\phi}}\right] = Q_\phi$ and $\left[\frac{\partial \xi_\phi}{\partial \phi}\right] = C_\phi$ 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 $M \in \Re^{nxn}$ and $B \in \Re^{nxn}$ 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 $Q_\phi, J_\phi, M, B \in \Re^{nxn}$, sufficient conditions for having unique solutions or control F is $rank(Q_\phi J_\phi) = n$.

IV. 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 give 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 d.o.f. systems.

Assume the dynamic model of master and slave system as:

$$m_i \ddot{x}_i - d_i = F_i - F_{iext}, i = m, s \quad (11)$$

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 $x_s = x_m$ and $F_m = -F_s$ in literature. Behavior of ideal bilateral system is defined as requirement that error in position (12) and the error in force (13) are zero.

$$\varepsilon_{x-}(t) = x_m(t) - x_s(t) \quad (12)$$

$$\varepsilon_{F+}(t) = F_s(t) + F_m(t) \quad (13)$$

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 (14) and (15).

$$\begin{aligned} \ddot{\varepsilon}_x &= \ddot{x}_m - \ddot{x}_s \\ \ddot{\varepsilon}_x &= F_m - F_s, \ddot{\varepsilon}_x = F_x \end{aligned} \quad (14)$$

$$\begin{aligned} \ddot{\varepsilon}_F &= \ddot{x}_m + \ddot{x}_s \\ \ddot{\varepsilon}_F &= F_m + F_s, \ddot{\varepsilon}_F = F_F \end{aligned} \quad (15)$$

Now selection of F_x and F_F is a simple task and the real control inputs are easily obtained [8] as: $F_m = \frac{1}{2}(F_x + F_F)$ and $F_s = \frac{1}{2}(F_F - F_x)$. 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.

In (14) and (15) 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 framework of the sliding mode systems. 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 (12) and (13) the selection of the force tracking manifold should be defined taking into consideration the impedance of the human operator as depicted in (16). 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 (16) just the slave side force can be used instead. The selection of the position tracking manifold is straight forward and is defined as in (17).

$$S_F = \{(x_m, x_s) : (C_h x_m + D_h \dot{x}_m) + (C_e x_s + D_e \dot{x}_s) = \sigma_F = 0\} \tag{16}$$

$$S_x = \{(x_m, x_s) : Q\dot{\varepsilon}_x + G_x \varepsilon_x = \sigma_x = 0\} \tag{17}$$

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 [12]. 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 is to be adjusted and that the impedance of environment may not be known (and generally is not) the force tracking manifold (16) can be rewritten in the following form

$$\begin{aligned} &S_F = \{(\varepsilon_{x^+}, \dot{\varepsilon}_{x^+}, x_s) : C_h \varepsilon_{x^+} + D_h \dot{\varepsilon}_{x^+} + (C_e - C_h) x_s + \\ &(D_e - D_h)\dot{x}_s = \sigma_F = 0\} \\ &\varepsilon_{x^+} = x_m + x_s \end{aligned} \tag{18}$$

$$\zeta(x_s, \dot{x}_s) = (C_e - C_h) x_s + (D_e - D_h)\dot{x}_s \tag{19}$$

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 is the sliding mode is enforced on the intersection of the above manifolds [17]:

$$S_B = \{(x_m, \dot{x}_m, x_s, \dot{x}_s) : S_x \cap S_F, \sigma_x \cap \sigma_F = 0\} \tag{20}$$

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

$$\dot{\sigma}_x = Q\ddot{\varepsilon}_x + G_x \dot{\varepsilon}_x \tag{21}$$

$$\dot{\sigma}_F = Q_x\big[\big(\tfrac{1}{m_m}F_m + \tfrac{1}{m_s}F_s\big) - \big(\tfrac{1}{m_m}d_m - \tfrac{1}{m_s}d_s\big)\big] + G_x \dot{\varepsilon}_x \tag{22}$$

$$\dot{\sigma}_F = (D_h \ddot{\varepsilon}_{x^+} + C_h \dot{\varepsilon}_{x^+}) + \zeta(x_s, \dot{x}_s) \tag{23}$$

$$\dot{\sigma}_F = D_h\big[\big(\tfrac{1}{m_m}F_m + \tfrac{1}{m_s}F_s\big) - \big(\tfrac{1}{m_m}d_m + \tfrac{1}{m_s}d_s\big)\big]\zeta(x_s, \dot{x}_s) \tag{24}$$

Equations (22) and (24) are representing simple first order systems with control being linear combination of the master and the slave control inputs. They can be rewritten in the form:

$$\dot{\sigma}_x = F_x + d_x \tag{25}$$

$$\dot{\sigma}_F = F_F + d_F \tag{26}$$

The selection of the controller for (25) and (26) like in (5) will satisfy the stability conditions and ensure that the sliding mode is enforced in intersection (20) thus ensuring the motion of the system in intersection of manifolds (16) and (17). That way the condition for the bilateral systems operation (12) and (13) 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 first order filter $\hat{d}_i = -g\sigma_i + (F_i - g\sigma_i)g/(s+g); i = x, F)$ and simple proportional controller. In this case asymptotic stability of the motion towards manifold is ensured and thus asymptotic stability of the (12) and (13). Both methods are satisfying at least exponential stability conditions. The different is in the fact that sliding mode guaranty finite time convergence thus the conditions (12) and (13) will be satisfied exactly for $t > t_0$ where t_0 is so-called reaching time. The disturbance observer can be combined with sliding mode control.

A. Simulation Results

In the simulation the effectiveness of the proposed control structure is investigated in the setting when master and slave are single DOF systems. The master side is by input force generated by operator driven to execute sinusoidal motion. The slave side is moving free or in contact with environment that is simulated to move with small sinusoidal oscillations. Frequency of that oscillation is higher that the frequency of the master side position motion thus the force developed by contact with obstacle may be time varying. The limit force on the slave side is set to be either constant or time varying in order to show that the proposed algorithm is capable of resolving the position tracking and force tracking requirements. In order to show the force tracking capability the system is simulated in the case when apparent impedance on the operators side and on the slave side equal and in the case when these impedances are different.

The simulation is performed in SIMNON assuming continuous plants and discrete time implementation of the controller. The parameters of the master and slave system and the references are as follows:

Master: $m_m = 0.2(1 + 0.25\sin(6\pi t))$
$d_m = 15(\cos \pi t + 3\sin 3\pi t) + T_{fm}$
$T_{fm} = 2sign(\dot{x}_m)$
Slave: $m_s = 0.1(1 + 0.25\sin(6\pi t))$
$d_s = 12(\cos \pi t + 3\sin 2\pi t) + T_{fs}$
$T_{fs} = 2sign(\dot{x}_s)$
Master position reference: $x_{mr} = 0.35\sin(24.58t)$
Obstacle: $x_o = 0.151(0.3sin(12t))$
Slave impedance: $C_e = 250, 1500\ D_e = 1.5, 5$
Operator impedance: $C_h = 250, 550\ D_h = 1.5, 5$
Slave side force limit: $F_r = 55(1 + 0.25\sin(8\pi t))$
Controller structure: as in (5) with $\Psi(\sigma) = -D\sigma$

Manifold parameters: $Q_x = 100$ $G_x = 150$
Controller parameters: $D = 100$
Sampling time: $T = 0.1ms$

In Fig. 1 the behavior of the system with equal impedances on the master and on the slave side is depicted. Slave impedance: $C_e = 250$, $D_e = 1.5$, master side impedance: $C_h = 250$, $D_h = 1.5$. It is shown that the position tracking and the force tracking is satisfactory.

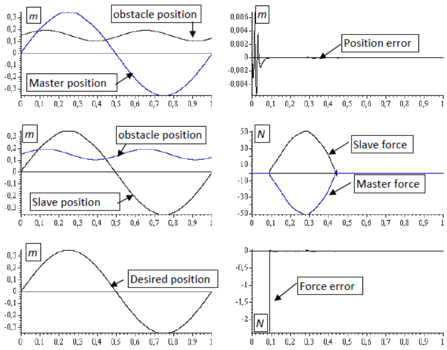

Fig. 1. The behavior of the system with the same mechanical impedance on the master and on the slave side. Diagram (1,1) depicts master position and the position of obstacle on the slave side, diagram (1.2) depicts master position and the position of obstacle on the slave side, diagram (1,3) depicts desired motion on the master side, diafram (2.1) depicts position tracking error, diagram (2,2) depicts master and slave side forces and diagram (2,3) depicts force tracking error

In Fig. 2 the same systems are depicted with different impedances on the master and on the slave side. Slave impedance: $C_e = 1500$, $D_e = 5$, master side (operator) impedance: $C_h = 550$, $D_h = 5$ and with the limit on the slave side force given as $F_r = 55(0.1 + 0.25\sin(8\pi t))$. The results confirm that proposed algorithm is achieving the desired behavior of the system. The force error appears due to the imposed motion on the master side by operator.

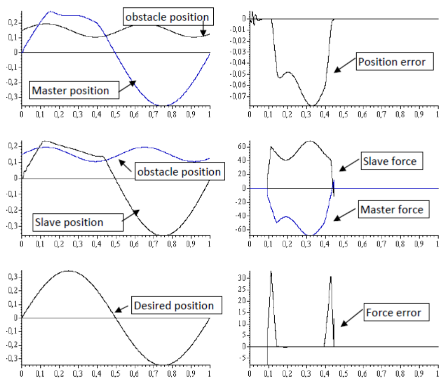

Fig. 2. The behavior of the system with diffrent mechanical impedance on the master and on the slave side. Diagram (1,1) depicts master position and the position of obstacle on the slave side, diagram (1.2) depicts master position and the position of obstacle on the slave side, diagram (1,3) depicts desired motion on the master side, diafram (2.1) depicts position tracking error, diagram (2,2) depicts master and slave side forces and diagram (2,3) depicts force tracking error

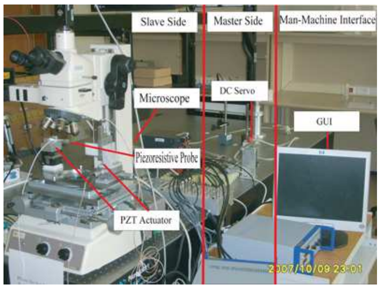

Fig. 3. Experimental Setup of Tele-Micromanipulation

V. 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 description of the experimental setup [13] is depicted in Figure 3.

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 [14] 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. Stictionless 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 [15]. 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. As for the force feedback, a piezoresistive AFM cantilever (from AppNano) has been utilized along with a custom built Wheatstone bridge. A real time capable

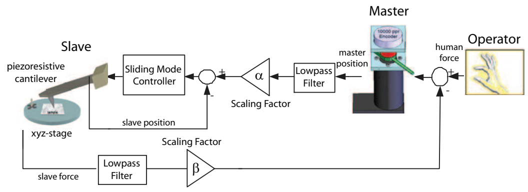

Fig. 4. Bilateral Control Structure

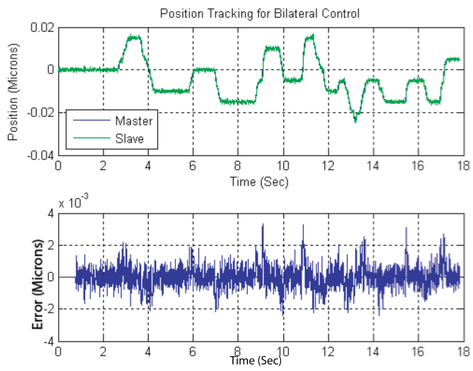

Fig. 5. Position responses and position error in the experiment

control card (dSPACE DS1103) is used as control platform and an optical microscope (Nikon MM-40) is used for visual feedback.

The overall structure of bilateral control utilized in tele-micromanipulation is depicted in Figure 4 [16].

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 m/deg and beta= 0.00366 N/nN are used, that is an angular displacement of 1deg on the master side corresponds to a linear displacement of 1m on the slave side and a force of 0.00366nN on the slave side corresponds to a force of 1N 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 before scaling.

A. Experimental Validation of Bilateral Control

Figure 5 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 $\pm 2 \times 10^{-8} m$ amplitude, the tracking error ranges between $\pm 2 \times 10^{-9} m$. 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.

VI. Conclusion

In this paper, we proposed that function based control can be used in controlling systems in interactions and establishing desired functional relations between systems. It has been showed that 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. Besides, 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 experimantal results encouraged that function based control appraoch can be applied on the micromanipulation setup.

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