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Decentralized robust control for teleoperated needle insertion with uncertainty and communication delay[☆]

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ABSTRACT

An iterative synthesizing strategy for robust force reflecting control of a Haptic exploration device is proposed. The proposed strategy guarantees the robust stability of the closed loop system with respect to uncertainties caused by the robot dynamics and environmental impedance as well as time-varying communication delays. In order to achieve the stability and performance objectives of the teleoperation system through a multiobjective optimization framework, a suboptimal robust controller is obtained with guaranteed global stability. Under a decentralized structure, the proposed approach provides a systematic design framework using $\mathcal{H}_\infty$ robust approach in the presence of interconnection in the structure. Through experimental results, the improved performance of the proposed approach is demonstrated.

1. Introduction

Needle insertion into soft tissues is a percutaneous procedure that has several clinical applications such as biopsy, brachytherapy, blood sampling, regional anesthesia, etc. [1]. An operator's ability to haptically explore a surgical environment is extremely important, as surgeons rely on Haptic sensation to detect embedded structures within tissues that are not visually observable, such as blood vessels, nerves, and tumors. In the needle insertion procedures, the effectiveness of treatment significantly depends on precisely placing the needle. It is proved that utilizing a master-slave teleopertion system results to more targeting accuracy of the needles [2]. The foremost objective of teleoperated needle insertion is position tracking in both free motion and during contact with soft tissues. In addition, it is proved that reflecting the environment contact forces to the master side improves the operator's performance and enhances task success rate [3,4]. Notwithstanding the mentioned positive aspect, the existence of force feedback in bilateral teleoperation systems endangers the system stability in the presence of communication time delay [5,6]. As an illustration, the force feedback creates a closed loop with time delay and as a result, the system stability becomes sensitive to time delay [7]. It is easy to see that without carefully designing of the compensator, any small time delay may destabilize the closed loop system. Therefore, the stability of the closed loop system in presence of such delays is very challenging in a teleoperation system. Moreover, in the teleoperated needle insertion, the environment dynamic model is nonlinear and subject to uncertainty. In literature reported on this issue, [8] and [9] presented dynamical models for needle insertion.

Up to now, several control architectures have been developed for teleoperation systems such as position-error-based PD control [10], adaptive control (e.g. [11,12]), model predictive control [13] and novel structures such as model-mediated (refer to survey [14]) or tele-matched design [15], and high fidelity microteleoperation designs [16]. However, in applications that the environment is supposed to be soft tissue, unstructured uncertainty of the environment is a very important challenge in the controller design. Most studies in the literature use the generic "ideal" teleoperator response as the performance objective. Yokokohji defined ideal response, in which the goal of the control design is to match the position and forces at the master and slave manipulators exactly or through a virtual impedance [17]. Lawrence defined transparency as the ratio between the transmitted and environment

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impedances [18]. His design goal was to keep this ratio close to one over a maximal bandwidth. Daniel and McAree [19] take into account considerations for improved stimulation of the tactile and kinesthetic receptors during teleoperator controller design by modifying the filter in the force feedback path. Colgate [20] introduced impedance-shaping bilateral control as a means of "constructively altering the impedance of a task", for improved perception by the user. In most of the works in the literature, passivity of the system (e.g[21,22].)or unconditional stability [23] is used as the means for ensuring the stability of the teleoperator, while it is coupled with arbitrary passive systems, environment, and operator. However, this condition is restrictive since the class of all possible passive systems is quite generic. If a more specific set of environment and human operator impedances are considered in the analysis, it may be possible to further increase the transparency of the system. Note that, transparency and robust stability are conflicting objectives in teleoperation systems in the presence of time delay [18]. For instance, in the case that the force feed back to the master is significantly attenuated, the teleoperation system does not have stablity problem but suffers from lack of transparency.

To deal with the unstructured uncertainties of the dynamical system in needle insertion procedure, a robust control approach is more effective than the other control methodologies. A quick literature review shows that several robust control architectures have been proposed for teleopertion systems. In [24], a μ-synthesis controller have been designed for teleoperation system. In [25], a μ-synthesis robust control is proposed for cooperative teleoperation systems and the experimental results show the effectiveness of the proposed approach. Park have proposed an energy-bounding approach to guarantee the robust system stability in variable time-delayed teleopation (e.g [26,27].). In [28] a robust impedance controller for a bilateral teleoperation under time delay is proposed using sliding surface. In [29], an adaptive inverse dynamic controller is utilized to suppress the system nonlinearities. Next, a robust controller based on recursive adobe problem is designed as the outer loop control to improve the system performance. However, the iterative synthesis of the proposed controller is complicated. To solve this problem, an LMI-based robust control approach is proposed in [30] for bilateral teleoperation systems. Note that, these approaches are developed for a general teleoperation system and not teleoperated needle insertion. Indeed, owing to the unstructured uncertainty of the environment, special design is required for teleoperated needle insertion systems. In [31], a robust controller is proposed for needle insertion into soft tissue which optimizes the fidelity of teleoperation system. Although, the optimization is only done for the controller parameters and not the controller structure. In fact, a fixed structure is presumed for the controller and its parameters are optimized according to the fidelity criterion.

Most of the conventional robust control approaches for teleopeation systems such as [31] and [28] are based on a global viewpoint of the teleoperation system using the nominal open loop transfer function and fidelity or transparency measures. In these approaches, the design procedure is done in a single step without considering the teleoperation subsystems individually. Generally, one drawback of the mentioned approaches is that the conditions for position tracking in free motion is required to prevent control parameters from yielding to trivial solutions [31]. This methodology imposes an extra condition to the design procedure which makes the controller synthesis more complicated. On the other hand, the previously stated robust control approaches for teleoperation systems can be categorized in two different groups. In the first group, a centralized control structure is developed based on the robust $\mathcal{H}_\infty$ approach (e.g. [24,29,30]). Note that, the centralized controllers need a powerful station to control the whole system. It is apparent that controlling the whole system from a central station give rise to practical problems due to some inevitable physical constraints such as time delay and packet loss in communication channels as well as the possibility of faults and failures in the central station. In the other category, a decentralized controller with a predefined structure is considered for the system and the controller parameters are tuned by optimizing the robust cost function (e.g. [31,28]). These approaches apply the optimization only on the control parameters and not the control structure. Therefore, the optimality of the controller among all stabilizing controllers is not ensured. As a result, it is valuable to have the positive aspects of both mentioned categories by developing a decentralized robust controller with optimization on the control structure. This is the major objective of this paper.

The main contribution of this paper is to propose a decentralized control scheme for teleoperated needle insertion, which simultaneously guarantees optimal nominal performance and robust stability. The proposed approach is capable to separately design the controllers in four consecutive steps which enhances the flexibility of the controller for designing in different scenarios. For instance, in some cases, optimal position tracking is more important than force tracking or vice versa. In the design procedure, the teleoperation system is initially divided into four sub-systems. Then, for each subsystem, a controller is designed sequentially. Controllers are initialized based on the $\mathcal{H}_\infty$ robust controller. The proposed method is continued by tuning controllers iteratively. By optimal remote position and force trackers which can be achieved by a sub-optimal solution, the system is proven to have highest possible transparency. Furthermore, robust stability of the entire system is proven by robustly controlled sub-systems with definite bounded uncertainty caused by environment dynamic and communication delays. To the best of our knowledge, this is the first decentralized controller synthesis for teleoperation systems which considers both remote position and force tracking in an iterative optimization framework. Preliminary outcomes of this research based on the simulation results were presented at an international conference [32]. This paper contains detailed steps of the control structure design, stability analysis of the entire system, and experimental evaluation of the proposed controller. In addition, the remote controllers (namely position and force tracking subsystems) are designed with a different perspective in which the effect of interconnection between these subsystems is considered systematically.

The rest of this paper is organized as follows. In Section 2, the basics of teleoperation systems and robust control are briefly illustrated. The proposed decentralized control structure is explained in Section 3. The detailed design procedure of the $\mathcal{H}_\infty$ control synthesis and the stability analysis of the global system are expressed in Section 4. The Experimental results of the proposed methodology are presented and compared with a fair counterpart with centralized approach in Section 5. Finally, the conclusions and future works are stated in Section 6.

2. Problem statement

A teleoperation system consists of master and slave manipulators, environment, communication channel and operator. Position and force tracking are the main control objectives of such system. These goals should be obtained in the presence of uncertainties in the dynamical models of the robots and the environment. Impedance control structure has been suggested in the situation where position tracking in free motion together with force tracking in contact is of great importance [28,33]. Without loss of generality, a nonlinear multi degrees of freedom (n-DOF) and a linear 1-DOF manipulator are respectively considered for master and slave robots. Master and slave dynamics are given by the following equations, respectively:

$$M_m\ddot{q}_m + C_m\dot{q}_m + G_m = u_m + J^{-T}\mathcal{F}_h,$$