Control of Networked Robotic System

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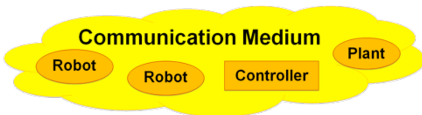
Motivation

- Several control applications focus on networked mechanical systems where the control loops between the mechanical systems or controllers and plants are closed over unreliable communication networks.
- These engineering systems are subjected to time delay and data losses that can potentially make these systems unstable and severely degrade control performance.



Introduction

- The problem of synchronizing networked mechanical systems has received considerable interest and is important for several applications such as cooperative manipulation or teleoperation.
- Task space synchronization of heterogeneous networked mechanical systems is important for cooperative control of mechanical systems.
- Passivity based control is used to study task space synchronization of networked multi-agent systems in the task-space.
- Robustness to time delays and disturbances is also examined.

Adaptive Trajectory Tracking

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+g(q)=u \quad \text{(Euler-Lagrange Dynamics)}$$

$$u(t)=\hat{M}(q)a(t)+\hat{C}(q,\dot{q})v(t)+\hat{g}(q)-K_t s(t)-J^T K_J^T\tilde{X}+J^T\tau$$

For non-redundant robots

$$v(t)=J^{-1}(\dot{X}^d-\Lambda(X-X^d))$$

$$a(t)=\dot{v}(t)=J^{-1}(\ddot{X}^d-\Lambda(\dot{X}-\dot{X}^d))+\dot{J}^{-1}(\dot{X}^d-\Lambda(X-X^d))$$

$$s(t)=J^{-1}(-\dot{X}^d+\Lambda(X-X^d))+\dot{q}$$

$$r(t)=Js(t)=(\dot{X}-\dot{X}^d)+\Lambda(X-X^d)=\dot{\tilde{X}}+\Lambda\tilde{X}$$

The above system is passive with a positive definite storage function $V(s,\tilde{X},\tilde{\Theta}_d)=\frac{1}{2}\left(s^T M s+\tilde{X}^T K_J\tilde{X}+\tilde{\Theta}_d^T\Gamma\tilde{\Theta}_d\right)$

Controlled Synchronization

Assume N agents, interconnected using a balanced and strongly connected communication graph. Let the output coupling control be given as

$$\tau_i(t)=\sum_{j\in\mathcal{N}_i}(r_j(t)-r_i(t)) \quad i=1,\ldots,N$$

Consider the positive definite storage function, $V(Z)=V_1(z_1)+\ldots+V_N(z_n)=\sum_{i=1}^{N}V_i(z_i)$

It is then possible to show that

$$\dot{V}=-\frac{1}{2}\sum_{i=1}^{\mathcal{N}}\sum_{j\in\mathcal{N}_i}(r_j-r_i)^T(r_j-r_i)-\sum_{i=1}^{\mathcal{N}}\left(s_i^T K_{ti}s_i+\tilde{X}_i^T K_{Ji}\Lambda_i\tilde{X}_i\right)\leq 0$$

Agents asymptotically synchronize in the task space.

Time delays can also be addressed in this framework.

$$\lim_{t\to\infty}\|r_j(t-T_{ji}^k)-r_i(t)\|=0 \quad \forall i,j,k$$

For redundant robots

If one or more agents are redundant manipulators, the control scheme can be modified as

$$a(t)=J^+(\ddot{X}^d-\Lambda(\dot{X}-\dot{X}^d))+\dot{J}^+(\dot{X}^d-\Lambda(X-X^d))-\frac{d}{dt}[(I-J^+J)\psi]$$

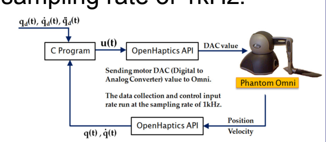
$$v(t)=J^+(\dot{X}^d-\Lambda(X-X^d))-(I_n-J^+J)\psi$$

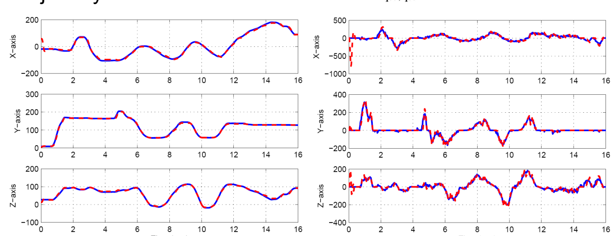
$$s(t)=J^+(-\dot{X}^d+\Lambda(X-X^d))-(I_n-J^+J)\psi+\dot{q}$$

Experimental Results

The controlled synchronization scheme is validated through the experiments on a Phantom Omni haptic device. Control programs are written in C, using OpenHaptics API with the sampling rate of 1kHz.

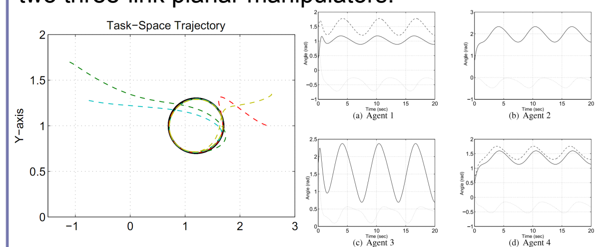
The position and velocity of the end-effector achieves synchronization even in the absence of the desired trajectory.



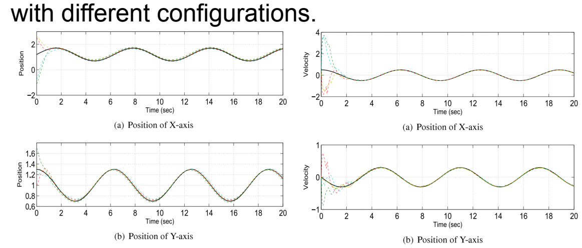


Simulation Results

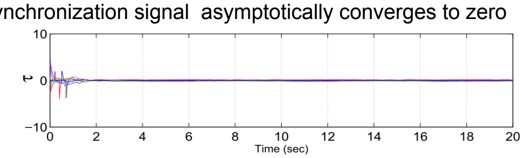
The controlled synchronization scheme is validated through the simulation on two two-link and two three-link planar manipulators.



Robots follow the same trajectory in task-space even with different configurations.



In the presence of time delays, the agents can achieve synchronization and also follow the desired trajectory. The synchronization signal asymptotically converges to zero



Future Works

- A theory of network control of mechanical systems is still in its infancy. The goal of the project is to develop a control framework to achieve stable control of networked robotic systems with high performance.
- To this end, we developed algorithms for task space synchronization of networked robotic systems. Future work will encompass extending the classical robot control algorithms for the network control scenario.