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Project for Physical Human Robot Interaction course A.Y. 2022-2023.

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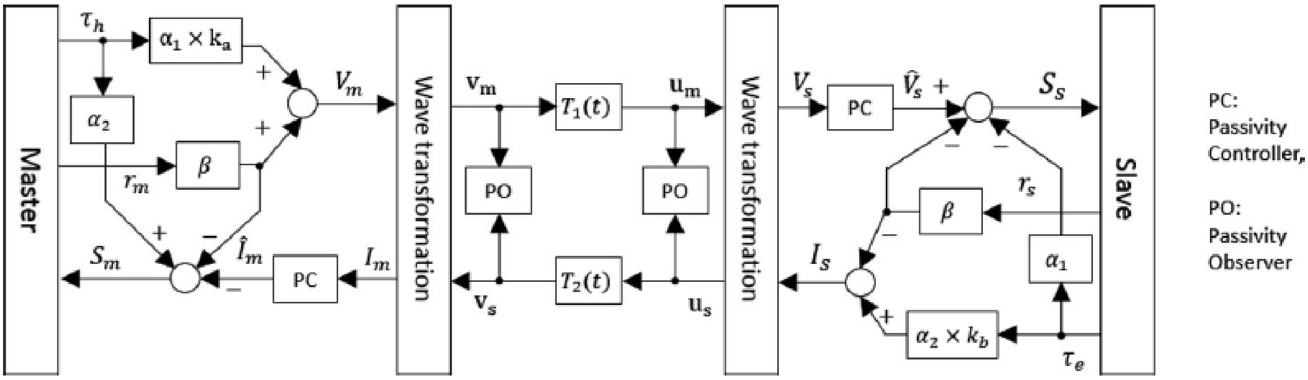
The scope of the project is to reproduce the 4-CH teleopration architecture proposed in the original paper:

D. Sun, F. Naghdy and H. Du, "Wave-Variable-Based Passivity Control of Four-Channel Nonlinear Bilateral Teleoperation System Under Time Delays," in IEEE/ASME Transactions on Mechatronics, vol. 21, no. 1, pp. 238-253, Feb. 2016, doi: 10.1109/TMECH.2015.2442586.



Major contributions of this paper:

1. Introduction of a new wave transformation that can be applied to a 4-CH architecture to achieve high transparency and channel passivity, even in the presence of constant time delays.
2. Development of a wave-based TDPA (Time-Delayed Passivity Approach) that guarantees system passivity even in the presence of time-varying delays.
3. Demonstration that the proposed system can achieve higher transparency compared to passivity-based systems from previous work while maintaining stability under random time delays.
4. Proof of the system stability in different environments.
5. Validation of the proposed algorithm's performance using the 3-DOF teleoperation system.

Contributions from 1 to 3 are reproduced in this project in a simplified scenario.

The "robot" implemented in this simulation is a very simple 1 DOF bar actuated by an electrical motor.

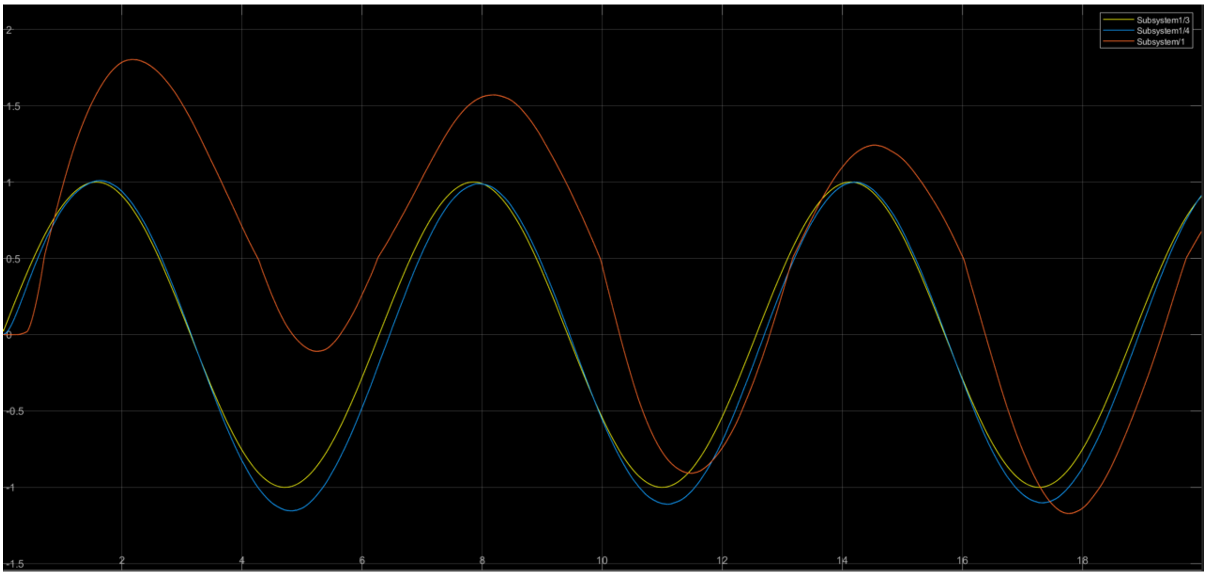
The implementation is made entirely in Matlab Simulink and use Level2 S-functions to create the passivity observer/controller described in the paper.

Results in constant and variable delay listed below.

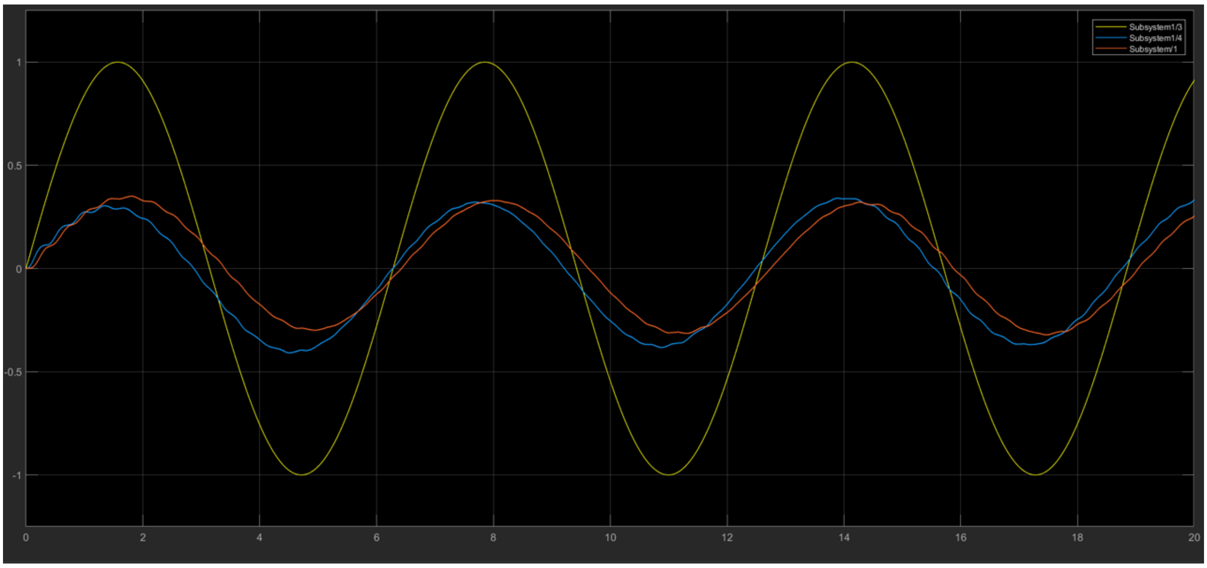
An ablation test has also been performed to verify the impact of each feature in the architecture.

Full architecture:

- Variable-time-delay:
  - Position:



- Constant-time-delay:
  - Position:



Passivity Observer and Controller

They have been implemented as Level2 S-Functions "pcon_m/s".m and "pobs_m/s.m" in line with equations described in the original paper.

- Passivity Observer:

$$
\begin{aligned}
P_{\text{obs}}^{m}(t) &= \frac{2}{1+B}u_m^T(t)\,u_m(t) + \frac{2}{M(1+B)}v_m^T(t)\,v_m(t) \\
&- \frac{1}{M(1+B)}\left(v_m(t) - Mu_m(t)\right)^T\left(v_m(t)\right. \\
&- \left. Mu_m(t)\right) - \frac{1}{M(1+B)}\varepsilon_1 v_m^T(t)\,v_m(t) \quad (44)
\end{aligned}
$$

$$
\begin{aligned}
P_{\text{obs}}^{s}(t) &= \frac{2}{B(1+B)}v_s^T(t)\,v_s(t) + \frac{2M}{1+B}u_s^T(t)\,u_s(t) \\
&- \frac{1}{M(1+B)}\left(v_s(t) + Mu_s(t)\right)^T\left(v_s(t)\right. \\
&+ \left. Mu_s(t)\right) - \frac{M}{1+B}\varepsilon_2 u_s^T(t)\,u_s(t) \qquad (45)
\end{aligned}
$$

where

$$
\varepsilon_{1,2} = \begin{cases} \dot{T}_{1,2}^{\text{estimate}}, & \text{if } \dot{T}_{1,2}^{\text{estimate}} \le 1 \\ 1, \text{else}, & \text{if } \dot{T}_{1,2}^{\text{estimate}} > 1. \end{cases} \qquad (46)
$$

- Passivity Controller:

$$
\begin{aligned}
\hat{I}_m(t) &= I_m(t) + \Gamma_1(t)\,V_m(t) \\
\hat{V}_s(t) &= V_s(t) + \Gamma_2(t)\,I_s(t)
\end{aligned}
$$

Coefficients for the controller:

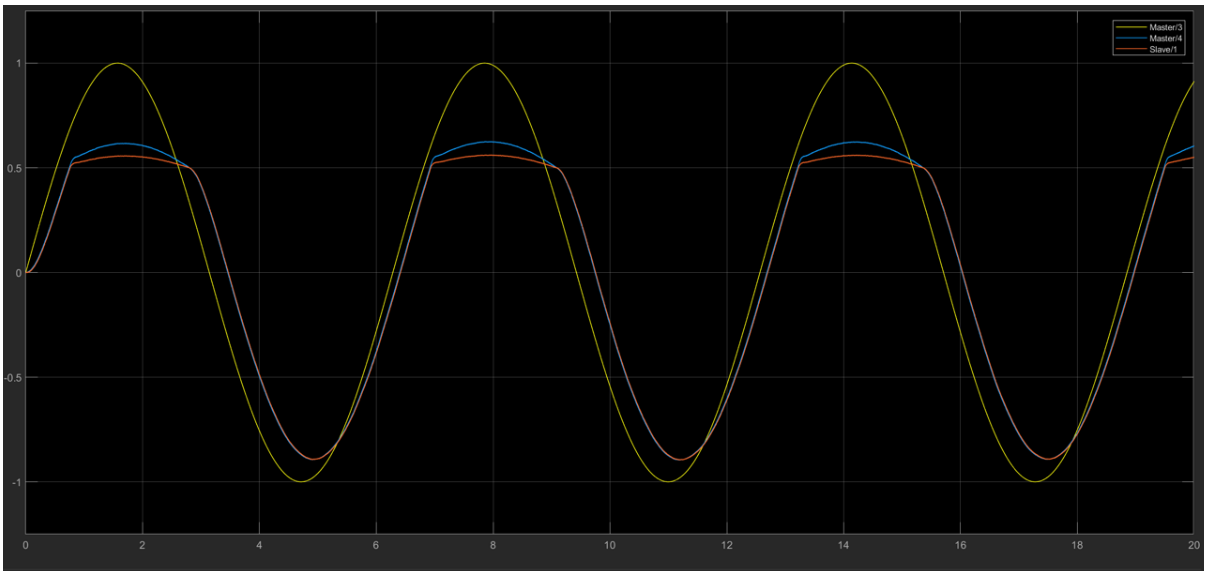
$$
\Gamma_1(t) = \begin{cases} 0, & \text{if } P_{\text{obs}}^{m}(t) > 0 \\ -P_{\text{obs}}^{m}(t)\left(V_m^T(t)\,V_m(t)\right)^{-1}, & \text{else, if } |V_m(t)| > 0 \end{cases} \qquad (49)
$$

$$
\Gamma_2(t) = \begin{cases} 0, & \text{if } P_{\text{obs}}^{s}(t) > 0 \\ P_{\text{obs}}^{s}(t)\left(I_s^T(t)\,I_s(t)\right)^{-1}, & \text{else, if } |I_s(t)| > 0. \end{cases}
$$

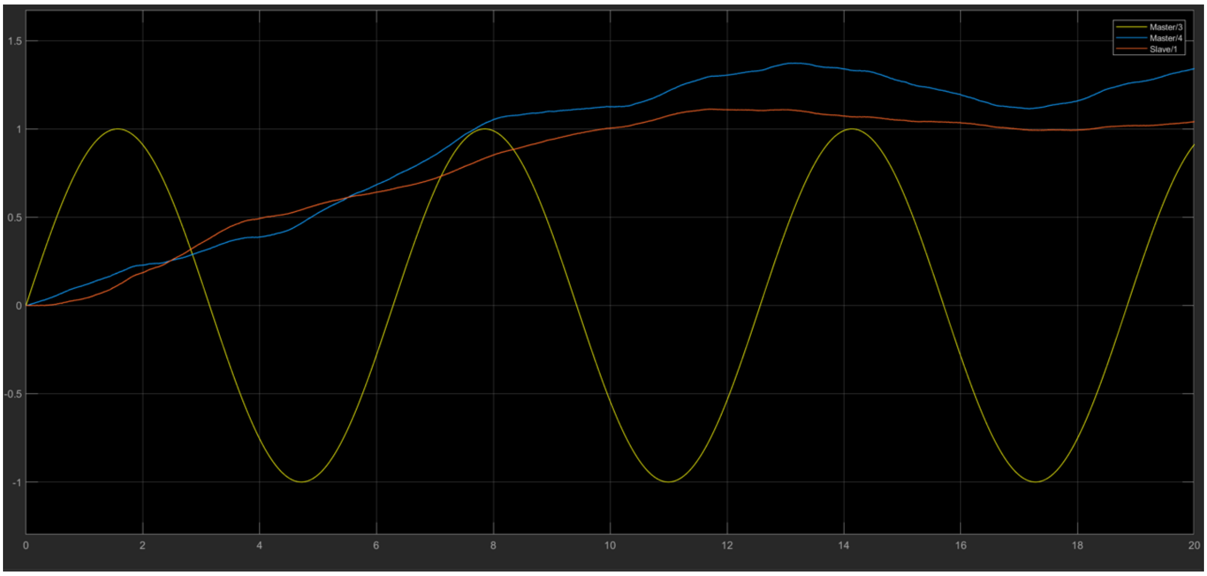
Ablation tests on position:

1. Base 4-CH architecture:

    - Constant delay:

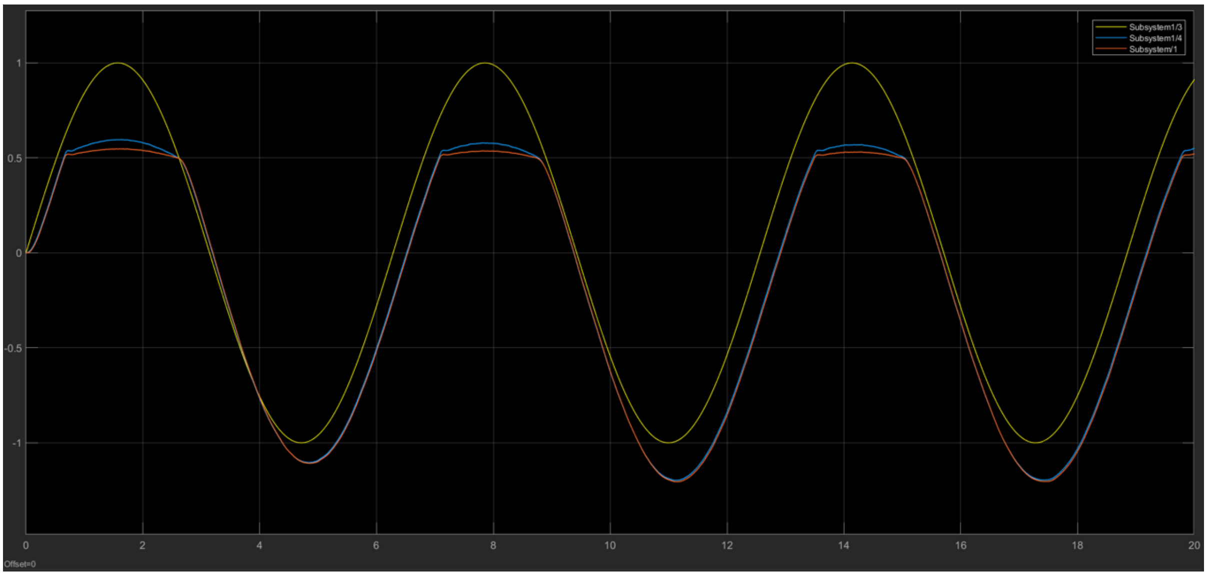
      

    - Variable Delay:

2. Classic wave-variables:

- Constant delay:



- Variable Delay: