Analysis of Linear Interface Algorithms for Power Hardware-in-the-Loop Simulation

Presented at the 2018 Grid Simulator Workshop

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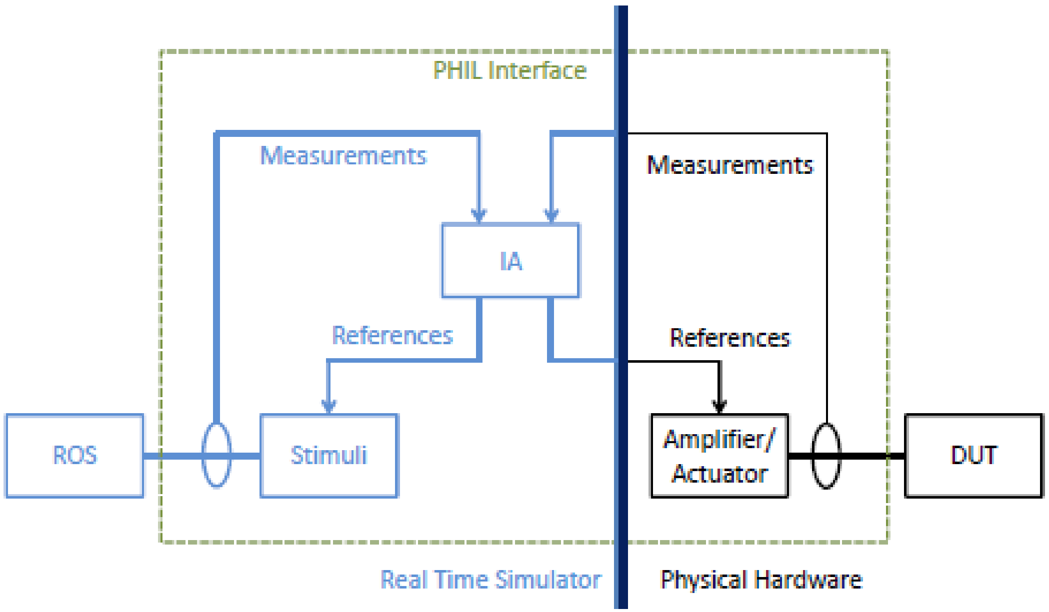
PHIL Interface

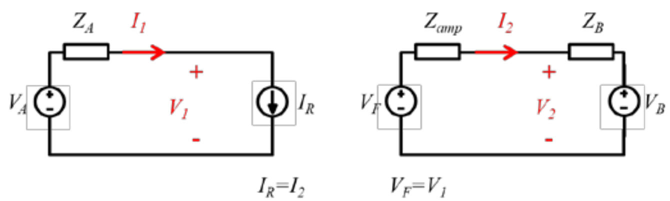
- PHIL interface consists of amplifier/actuator along with an interface algorithm (IA)
- IA ensures coupling between the ROS and the DUT
- IA typically implemented on digital real-time simulator (DRTS)
- IA makes use of simulated and physical measurements
- IA provides references to amplifier and stimuli
- Active area of research for PHIL



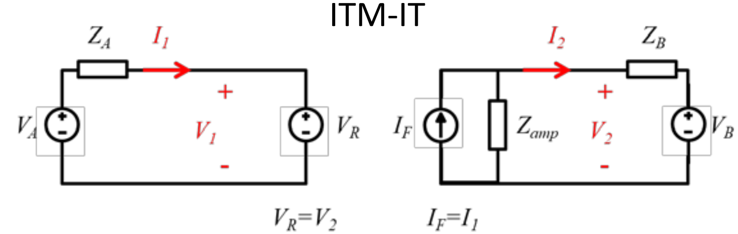
Role of the PHIL Interface Algorithm

Common PHIL Interface Algorithms in the Literature

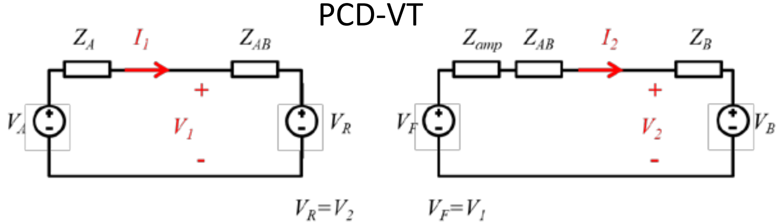
ITM-VT



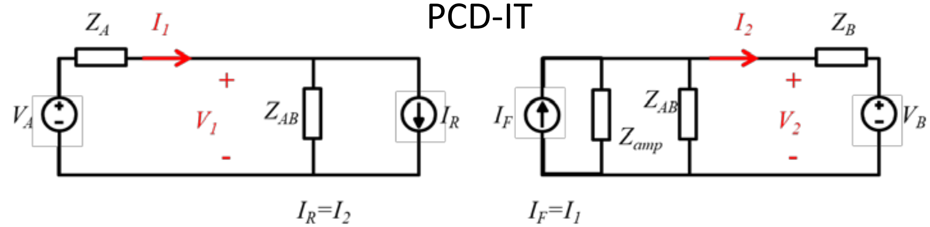
ITM-IT



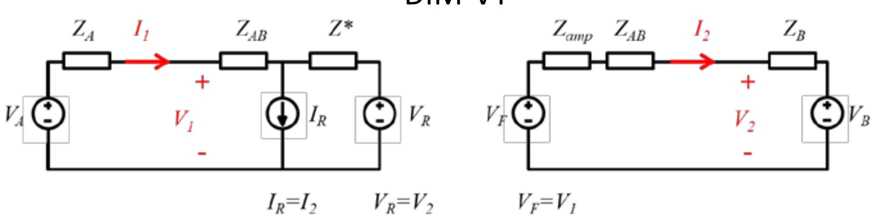
PCD-VT



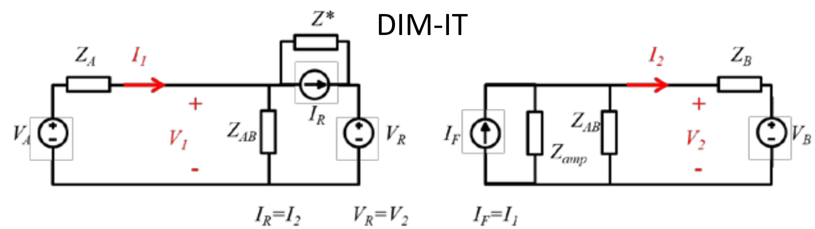
PCD-IT



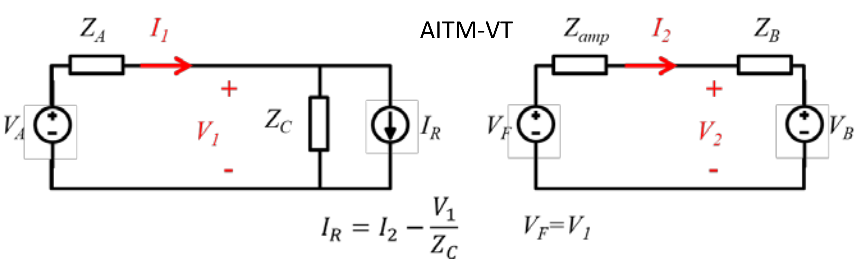
DIM-VT



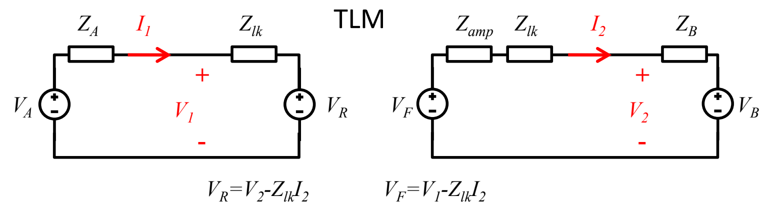
DIM-IT



AITM-VT



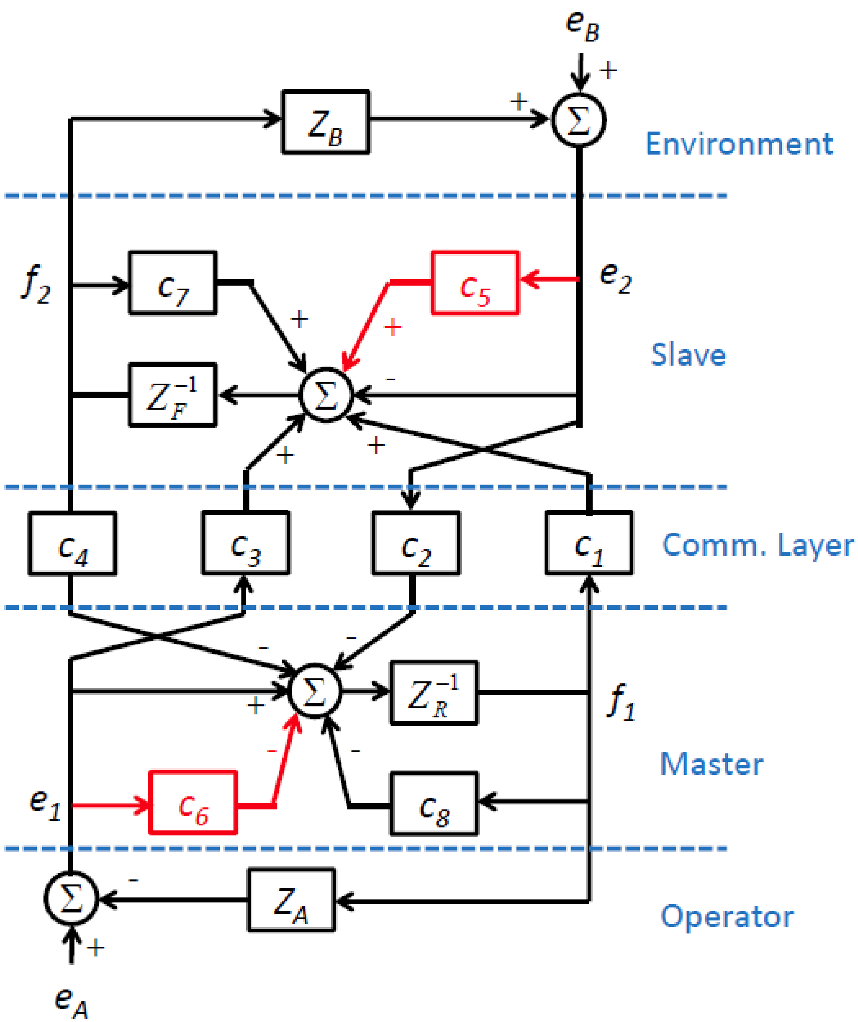
TLM



[1] G. Lauss, M. O. Faruque, K. Schoder, C. Dufour, A. Viehweider, and J. Langston. Characteristics and design of power hardware-in-the-loop simulations for electrical power systems. *IEEE Transactions on Industrial Electronics*, 63(1):406{417, Jan 2016.

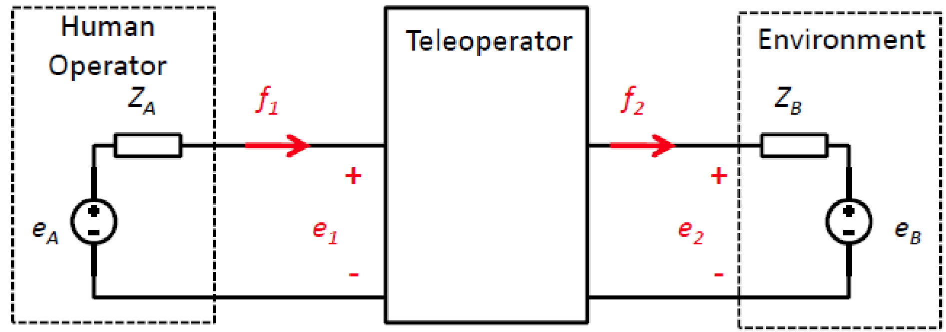
[2] C.S. Edrington, M. Steurer, J. Langston, T. El-Mezyani, and K. Schoder. Role of power hardware in the loop in modeling and simulation for experimentation in power and nergy systems. *Proceedings of the IEEE*, 103(12):2401{2409, Dec 2015.

Extended Lawrence Architecture (ELA)



Extended Lawrence Architecture [1]

[1] E. Naerum and B. Hannaford. Global transparency analysis of the Lawrence teleoperator architecture. In *Robotics and Automation*, 2009. ICRA '09. IEEE International Conference on, pages 4344–4349, May 2009.



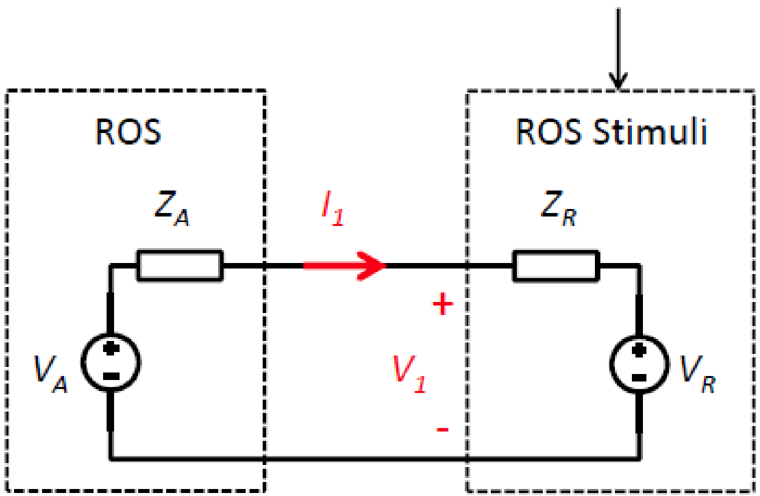
- Initially proposed by Lawrence (1993) [2]and extended by Hastrudi-Zaad and Salcudean (1999) [3].
- Generalizes and encompasses a number of proposed teleoperation IAs
- Z_R and Z_F account for impedance of master and slave manipulators
- Gains c_1, c_2, c_3, and c_4 provide for communication of effort and flow between the master and slave

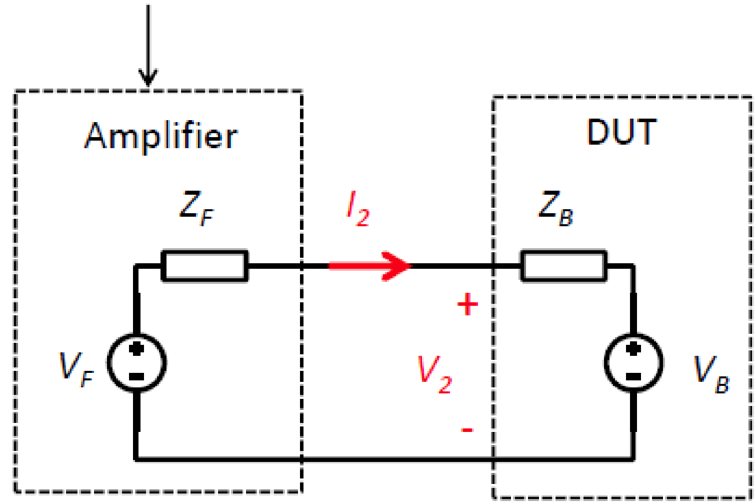
[2] D. A. Lawrence. Stability and transparency in bilateral teleoperation. IEEE Transactions on Robotics and Automation, 9(5):624{637, Oct 1993.

[3] K. Hastrudi-Zaad and S. E. Salcudean. On the use of local force feedback for transparent teleoperation. In Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No.99CH36288C), volume 3, pages 1863{1869 vol.3, 1999.

Applying the ELA to PHIL

$$V_{R-ref} = T^*_{1R}V_1 + Z^*_{1R}I_1 + T^*_{2R}V_2 + Z^*_{2R}I_2 \qquad V_{F-ref} = T^*_{1F}V_1 + Z^*_{1F}I_1 + T^*_{2F}V_2 + Z^*_{2F}I_2$$





$$V_R = T_{1R}V_1 + Z_{1R}I_1 + T_{2R}V_2 + Z_{2R}I_2 \qquad V_F = T_{1F}V_1 + Z_{1F}I_1 + T_{2F}V_2 + Z_{2F}I_2$$

$$\begin{array}{cc}
e_A \to V_A & e_B \to V_B \\
e_1 \to V_1 & e_2 \to V_2 \\
f_1 \to I_1 & f_2 \to I_2 \\
c_1 \to Z_{1F} & c_2 \to T_{2R} \\
c_3 \to T_{1F} & c_4 \to Z_{2R} \\
c_6 \to T_{1R} & c_5 \to T_{2F} \\
c_8 \to Z_{1R} & c_7 \to Z_{2F}
\end{array}$$

$$\begin{array}{ll}
T_{1F} = T_{mS}\,T_{amp}\,T^*_{1F} & Z_{1F} = T_{mS}\,T_{amp}\,Z^*_{1F} \\
T_{2F} = T_{mV}\,T_{amp}\,T^*_{2F} & Z_{2F} = T_{mI}\,T_{amp}\,Z^*_{2F} \\
T_{1R} = T_{mS}\,T_{stim}\,T^*_{1R} & Z_{1R} = T_{mS}\,T_{stim}\,Z^*_{1R} \\
T_{2R} = T_{stim}\,T_{mV}\,T^*_{2R} & Z_{2R} = T_{stim}\,T_{mI}\,Z^*_{2R}
\end{array}$$

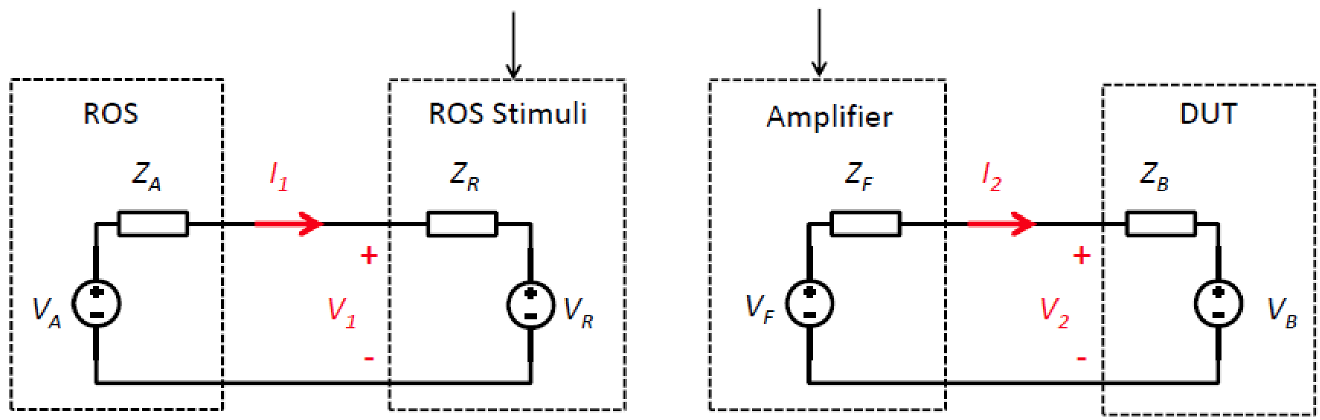
Existing PHIL IAs in the Context of the ELA

PHIL IA	T^*_{1R}	Z^*_{1R}	T^*_{2R}	Z^*_{2R}	T^*_{1F}	Z^*_{1F}	T^*_{2F}	Z^*_{2F}	Z_R	Z_F
ITM-VT	0	0	0	$-Z_R$	1	0	0	0	Z_R	Z_{amp}
ITM-IT	0	0	1	0	0	Z_{amp}	0	0	0	Z_{amp}
PCD-VT	0	0	1	0	1	0	0	0	Z_{AB}	$Z_{AB}+Z_{amp}$
PCD-IT	0	0	0	$-Z_{AB}$	0	$Z_{AB}//Z_{amp}$	0	0	Z_{AB}	$Z_{AB}//Z_{amp}$
DIM-VT	0	0	1	$-Z^*$	1	0	0	0	Z^*+Z_{AB}	$Z_{AB}+Z_{amp}$
DIM-IT	0	0	Q_1 (25)	$-Z^*//Z_{AB}$	0	$Z_{AB}//Z_{amp}$	0	0	$Z^*//Z_{AB}$	$Z_{AB}//Z_{amp}$
TLM	0	0	1	$-Z_{lk}$	1	Z_{lk}	0	0	Z_{lk}	$Z_{lk}+Z_{amp}$
AITM-VT	1	0	0	$-Z_C$	1	0	0	0	Z_C	Z_{amp}

$$Q_1 = \frac{Z_{AB}}{Z^*+Z_{AB}}$$

$$V_{R-ref} = T^*_{1R}V_1 + Z^*_{1R}I_1 + T^*_{2R}V_2 + Z^*_{2R}I_2$$

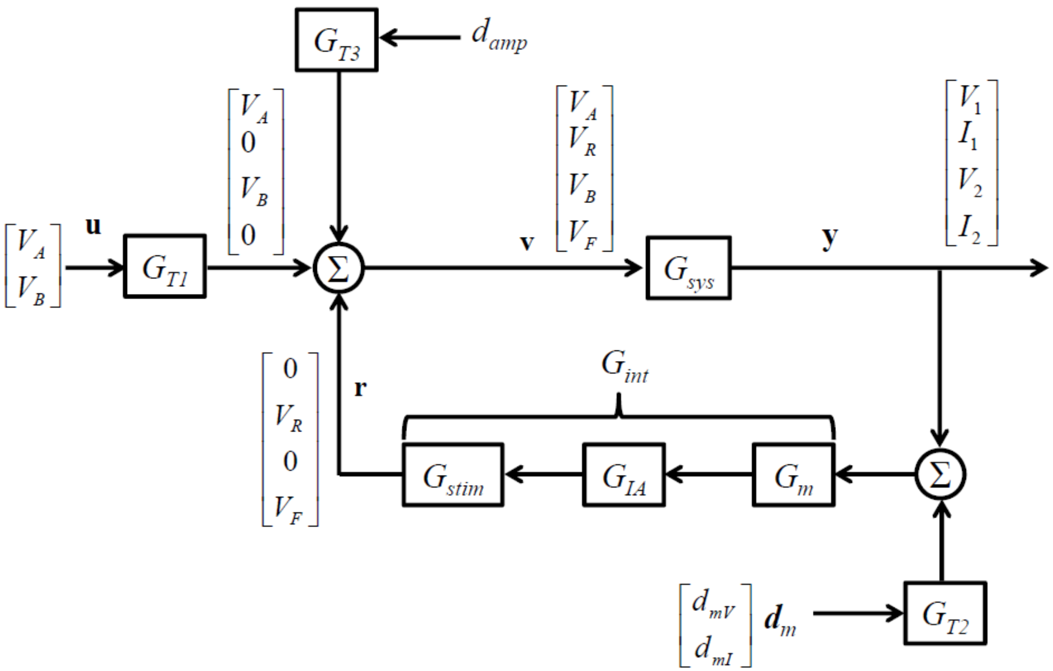
$$V_{F-ref} = T^*_{1F}V_1 + Z^*_{1F}I_1 + T^*_{2F}V_2 + Z^*_{2F}I_2$$



$$V_R = T_{1R}V_1 + Z_{1R}I_1 + T_{2R}V_2 + Z_{2R}I_2$$

$$V_F = T_{1F}V_1 + Z_{1F}I_1 + T_{2F}V_2 + Z_{2F}I_2$$

Compact Formulation of a PHIL Simulation Experiment in the Context of the ELA



$$G_m = \begin{bmatrix} T_{mS} & 0 & 0 & 0 \\ 0 & T_{mS} & 0 & 0 \\ 0 & 0 & T_{mV} & 0 \\ 0 & 0 & 0 & T_{mI} \end{bmatrix}$$

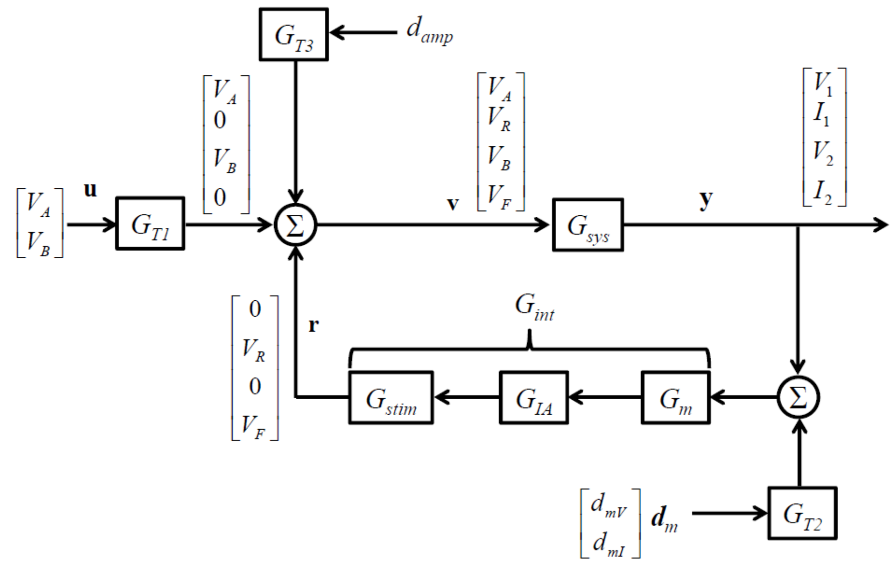
$$G_{IA} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ T_{1R}^* & Z_{1R}^* & T_{2R}^* & Z_{2R}^* \\ 0 & 0 & 0 & 0 \\ T_{1F}^* & Z_{1F}^* & T_{2F}^* & Z_{2F}^* \end{bmatrix}$$

$$G_{stim} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & T_{stim} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & T_{amp} \end{bmatrix}$$

$$G_{sys} = \begin{bmatrix} \frac{Z_R}{Z_A + Z_R} & \frac{Z_A}{Z_A + Z_R} & 0 & 0 \\ \frac{1}{Z_A + Z_R} & -\frac{1}{Z_A + Z_R} & 0 & 0 \\ 0 & 0 & \frac{Z_F}{Z_B + Z_F} & \frac{Z_B}{Z_B + Z_F} \\ 0 & 0 & -\frac{1}{Z_B + Z_F} & \frac{1}{Z_B + Z_F} \end{bmatrix}$$

$$G_{int} = G_{stim} \, G_{IA} \, G_m = \begin{bmatrix} 0 & 0 & 0 & 0 \\ T_{1R} & Z_{1R} & T_{2R} & Z_{2R} \\ 0 & 0 & 0 & 0 \\ T_{1F} & Z_{1F} & T_{2F} & Z_{2F} \end{bmatrix}$$

Relevant Transfer Functions



Provided $\det(I - G_{sys}\,G_{int}) \neq 0$

Used for Assessment of Stability

$$G_{st} = -1 + \det(I - G_{sys}\,G_{int}) = -1 + \det(I - G_{int}\,G_{sys})$$

$$T_{u-y} = (I - G_{sys}\,G_{int})^{-1}\,G_{sys}\,G_{T1} = \left[\begin{array}{c|c} T_{u1-y1} & T_{u2-y1} \\ \hline T_{u1-y2} & T_{u2-y2} \end{array}\right] = \begin{bmatrix} T_{u1-V1} & T_{u2-V1} \\ T_{u1-I1} & T_{u2-I1} \\ T_{u1-V2} & T_{u2-V2} \\ T_{u1-I2} & T_{u2-I2} \end{bmatrix}$$

Used for Assessment of Accuracy

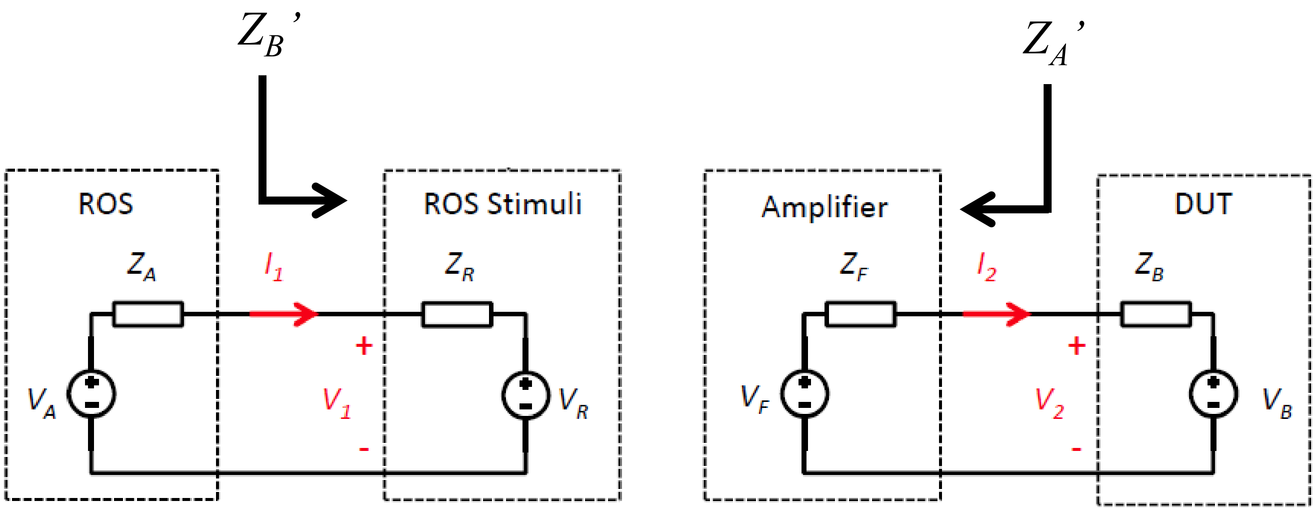
$$T_{damp-y} = (I - G_{sys}\,G_{int})^{-1}\,G_{sys}\,G_{T3} = \begin{bmatrix} T_{damp-y1} \\ \hline T_{damp-y2} \end{bmatrix} = \begin{bmatrix} T_{damp-V1} \\ T_{damp-I1} \\ T_{damp-V2} \\ T_{damp-I2} \end{bmatrix}$$

Used for Assessment of Sensitivity to Disturbances

$$T_{dm-y} = (I - G_{sys}\,G_{int})^{-1}\,G_{sys}\,G_{int}\,G_{T2} = \begin{bmatrix} T_{dm-y1} \\ \hline T_{dm-y2} \end{bmatrix} = \begin{bmatrix} T_{dmV-V1} & T_{dmI-V1} \\ T_{dmV-I1} & T_{dmI-I1} \\ T_{dmV-V2} & T_{dmI-V2} \\ T_{dmV-I2} & T_{dmI-I2} \end{bmatrix}$$

Used for Assessment of Sensitivity to Sensor Noise

Apparent Impedance



$$V_R = T_{1R}V_1 + Z_{1R}I_1 + T_{2R}V_2 + Z_{2R}I_2$$

$$V_F = T_{1F}V_1 + Z_{1F}I_1 + T_{2F}V_2 + Z_{2F}I_2$$

$$T_{u-y} = (I - G_{sys}\,G_{int})^{-1}\,G_{sys}\,G_{T1} = \left[\begin{array}{c|c} T_{u1-y1} & T_{u2-y1} \\ \hline T_{u1-y2} & T_{u2-y2} \end{array}\right] = \begin{bmatrix} T_{u1-V1} & T_{u2-V1} \\ T_{u1-I1} & T_{u2-I1} \\ T_{u1-V2} & T_{u2-V2} \\ T_{u1-I2} & T_{u2-I2} \end{bmatrix}$$

$$\boxed{Z'_B = \frac{T_{u1-V1}}{T_{u1-I1}}}$$

$$\boxed{Z'_A = \frac{T_{u2-V2}}{-T_{u2-I2}}}$$

Transparency Requirements for ELA IAs

I. At least two of the communication layer gains must be non-zero

II. At least two channels are complimentary, in the sense that effort and flow are sent in opposite directions across the communication layer (i.e. two nonzero gains must be either (Z_{1F},T_{2R}) or (T_{1F},Z_{2R})).

$$Z_{1F} = Z_F - Z_{2F}$$
$$T_{2R} = 1 - T_{1R}$$
$$T_{1F} = 1 - T_{2F}$$
$$Z_{2R} = -(Z_R + Z_{1R})$$

$$Z_{1F}T_{2R} - T_{1F}Z_{2R} \neq 0$$

- Note that these are necessary conditions, but not sufficient
- These can rule out some algorithms as not being able to achieve transparency
- Note that this is based on finite impedance for the amplifier and stimulus to simulated system

[1] E. Naerum and B. Hannaford. Global transparency analysis of the Lawrence teleoperator architecture. In *Robotics and Automation*, 2009. ICRA '09. IEEE International Conference on, pages 4344–4349, May 2009.

Initial Observations Regarding Transparency

PHIL IA	T^*_{1R}	Z^*_{1R}	T^*_{2R}	Z^*_{2R}	T^*_{1F}	Z^*_{1F}	T^*_{2F}	Z^*_{2F}	Z_R	Z_F
ITM-VT	0	0	0	$-Z_R$	1	0	0	0	Z_R	Z_{amp}
ITM-IT	0	0	1	0	0	Z_{amp}	0	0	0	Z_{amp}
PCD-VT	0	0	1	0	1	0	0	0	Z_{AB}	$Z_{AB} + Z_{amp}$
PCD-IT	0	0	0	$-Z_{AB}$	0	$Z_{AB}//Z_{amp}$	0	0	Z_{AB}	$Z_{AB}//Z_{amp}$
DIM-VT	0	0	1	$-Z^*$	1	0	0	0	$Z^* + Z_{AB}$	$Z_{AB} + Z_{amp}$
DIM-IT	0	0	Q_1 (25)	$-Z^*//Z_{AB}$	0	$Z_{AB}//Z_{amp}$	0	0	$Z^*//Z_{AB}$	$Z_{AB}//Z_{amp}$
TLM	0	0	1	$-Z_{lk}$	1	Z_{lk}	0	0	Z_{lk}	$Z_{lk} + Z_{amp}$
AITM-VT	1	0	0	$-Z_C$	1	0	0	0	Z_C	Z_{amp}

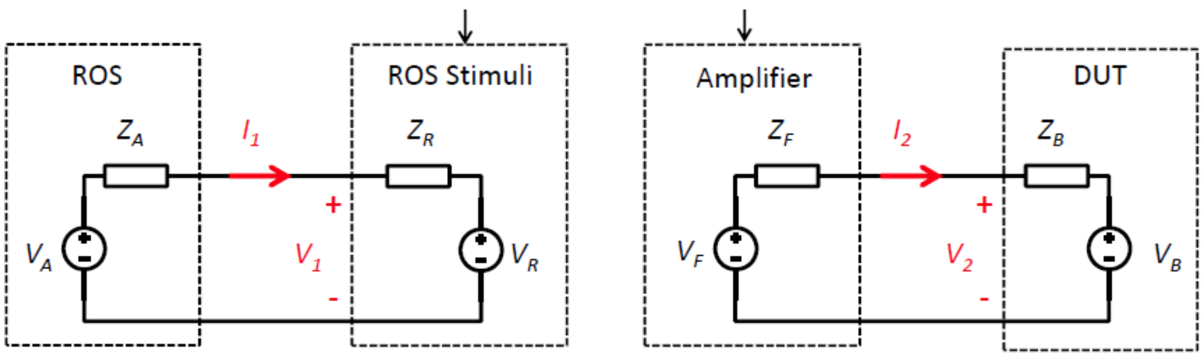
- Only the TLM IA makes use of 4 non-zero gains
- PCD-VT and PCD-IT violate Corollary 2

These IAs have been used successfully!

Considerations for Transparency of PHIL IAs: Conditions for Relaxation of Requirements

- Assumption for transparency requirements is that Z_F and Z_R are finite and non-zero.
- Generally valid assumption for teleoperation system, but not for PHIL simulation
- In PHIL simulation, Z_R is simulated, and can be ideal.
- In many practical cases (within a bandwidth of interest), the amplifier impedance (and Z_F) may be negligible

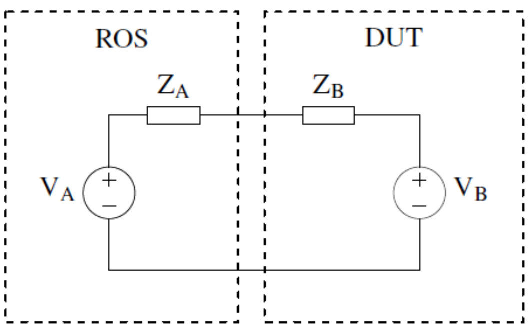
$$Z_{1F} = Z_F - Z_{2F}$$
$$T_{2R} = 1 - T_{1R}$$
$$T_{1F} = 1 - T_{2F}$$
$$Z_{2R} = -(Z_R + Z_{1R})$$

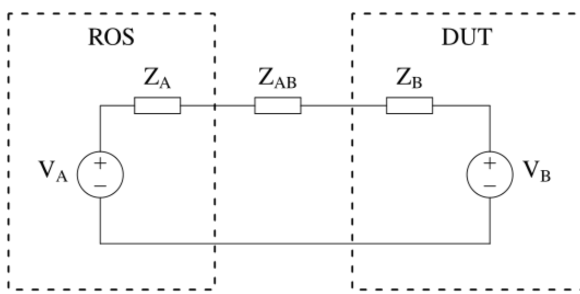


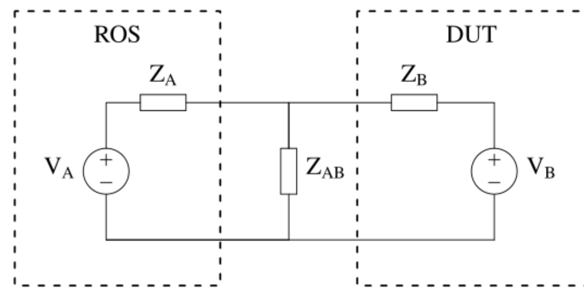
Considerations for Transparency of PHIL IAs: Interpretation of Transparency

- Some PHIL IAs represent linking impedances (e.g. PCD, DIM)
- The ideal *H* matrix is different for these
- Transparency may not represent ideal case

$$\begin{bmatrix} V_1 \\ -I_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix}$$







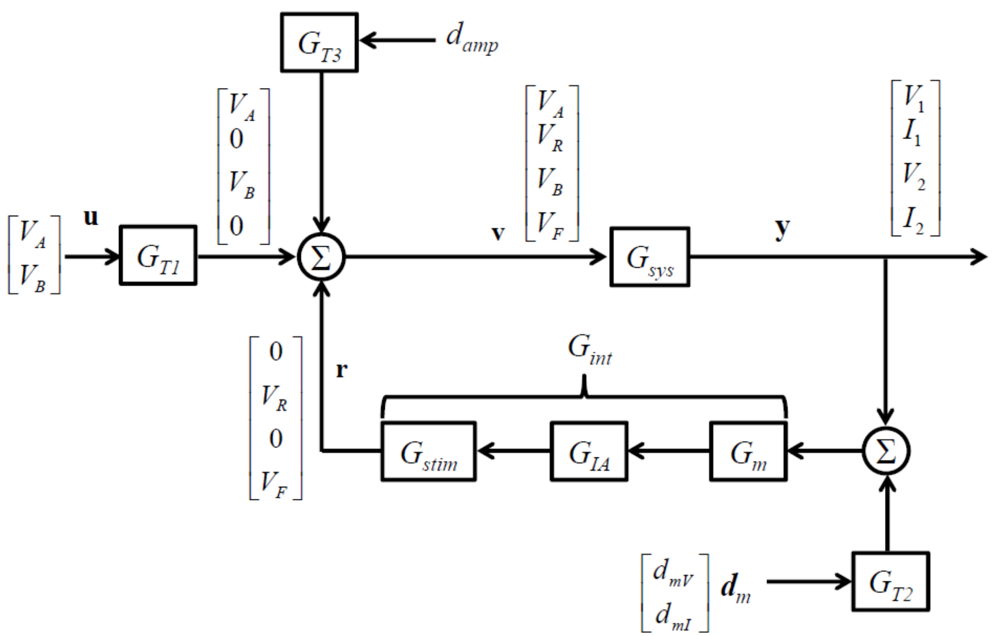
$$H_{ideal} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}$$

$$H_{ideal} = \begin{bmatrix} Z_{AB} & 1 \\ -1 & 0 \end{bmatrix}$$

$$H_{ideal} = \begin{bmatrix} 0 & 1 \\ -1 & \frac{1}{Z_{AB}} \end{bmatrix}$$

Considerations for Transparency of PHIL IAs: Asymmetries of PHIL Simulation Experiments

- Disturbances and noise injections occur in amplification and measurement of physical quantities
- Delays associated with T_{mS}, T_{stim}, T_{mV}, and T_{mI} are typically much smaller than the delay introduced by T_{amp}.
- Bandwidths of sensors are typically much higher than that of the amplifier
- Z_R is simulated, providing high degree of flexibility compared with Z_F



Conclusion and Future Work

- The ELA serves as framework for expression and analysis of linear PHIL Simulation IAs
- Distinctions between PHIL simulations and teleoperation systems
- Analysis of transparency yields important insights into PHIL IAs
- Full system (including ROS and DUT) important for full analysis
- Examination of existing IAs provides insight into the conditions for which performance is good and conditions for which performance is poor
- ELA as IA module

Future Work

- Derive framework, expressions, and metrics for multi-phase systems
- Derive framework, expressions, and metrics for multi-interface systems
- Further investigate application of IAs from teleoperation systems

Thank You