[1]University of Lincoln, UK [2]University of Padua, Italy [3]National Research Council of Italy

ROS-Causal: A ROS-based Causal Analysis Framework for Human-Robot Interaction Applications

Luca Castri[1], Gloria Beraldo[2,3], Sariah Mghames[1], Marc Hanheide[1], Nicola Bellotto[1,2]

{lcastri, smghames, mhanheide}@lincoln.ac.uk, gloria.beraldo@cnr.it, nbellotto@dei.unipd.it

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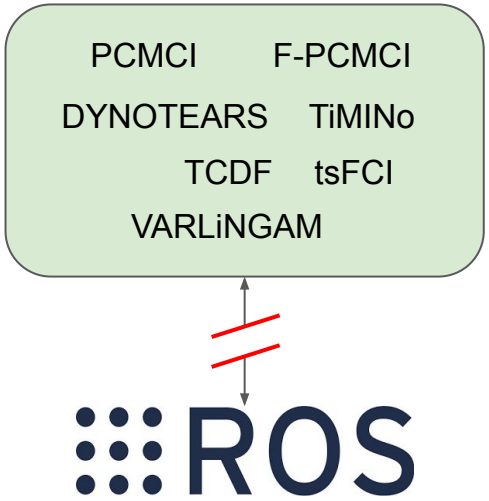
Motivation and Contribution

- Exploiting robots in many activities where the environment is shared with humans needs the development of new approaches for effective human-robot interactions (HRIs);
- Causal inference, the study of cause-and-effect relationships, can be a key factor in enhancing HRIs. However, most causal discovery methods for time-series data available in the literature lack integration with the Robot Operating System (ROS[1]), posing challenges:
  - these methods are incapable of running directly on the robot;
  - data collection and subsequent offline causal analysis are required;
  - the inability to exploit the built causal models in real-time.



[1]https://www.ros.org/

[1] Judea Pearl. 2009. Causality. Cambridge university press.

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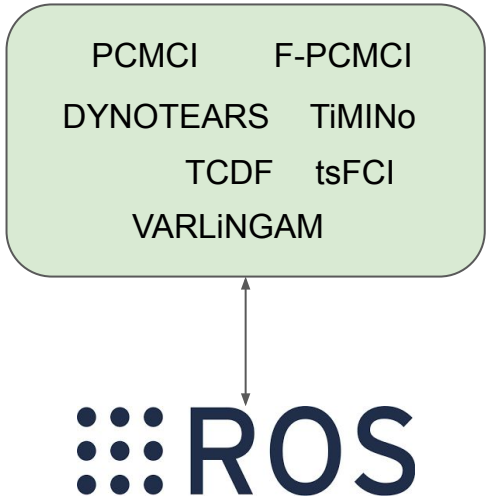
Motivation and Contribution

- Our contributions are:
  - the first ROS-based causal analysis framework designed for onboard data collection and causal discovery on robots: **ROS-Causal**;
  - an ad-hoc simulator for human-robot interactions to facilitate the design of HRI scenarios and to collect observational and interventional data for causal analysis: **ROS-Causal_HRISim**
  - an experimental evaluation of the proposed approach within the simulated environment to demonstrate its feasibility.

ROS-Causal

ROS-Causal_HRISim



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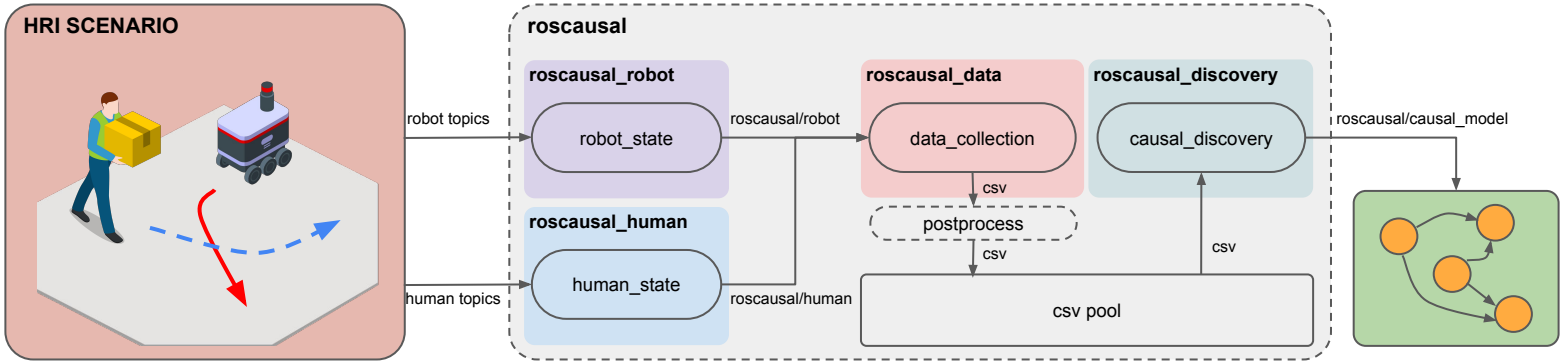
ROS-based Causal Analysis Framework



- ROS-Causal extracts and collects data from a HRI scenario, such as agents' trajectories, and performs causal analysis on the collected data in a batched manner. It is composed by four different rosnodes:
  - roscausal_robot
  - roscausal_human
  - roscausal_data
  - roscausal_discovery

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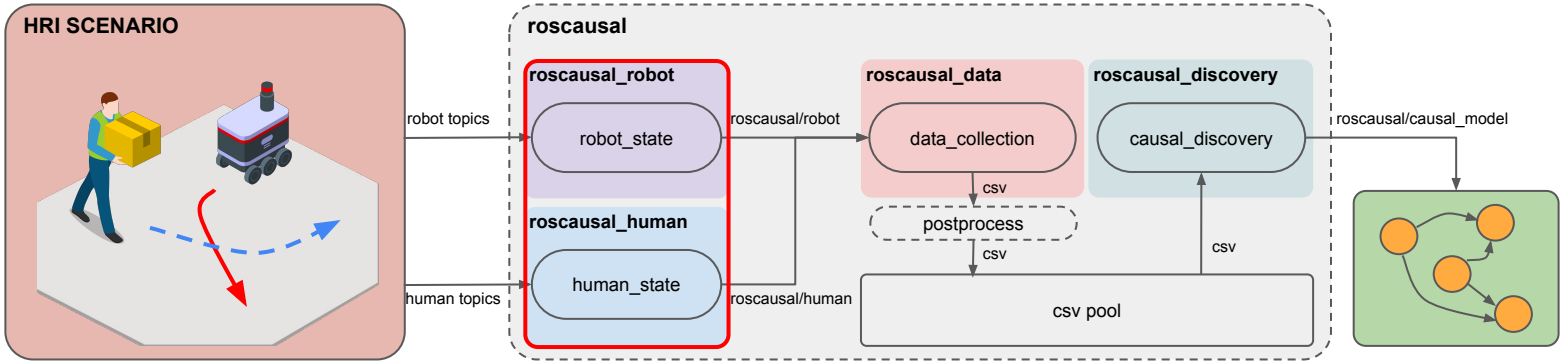
ROS-based Causal Analysis Framework



- ROS-Causal is composed by four different rosnodes:
  - **roscausal_robot**: collects data from several rostopics related to the robot (e.g., position, velocity, target position, etc.), and merge them into a single rostopic: *`roscausal/robot`*
  - **roscausal_human**: collects data from several rostopics related to the human (e.g., position, velocity, target position, etc.), and merge them into a single rostopic: *`roscausal/human`*
  - roscausal_data
  - roscausal_discovery

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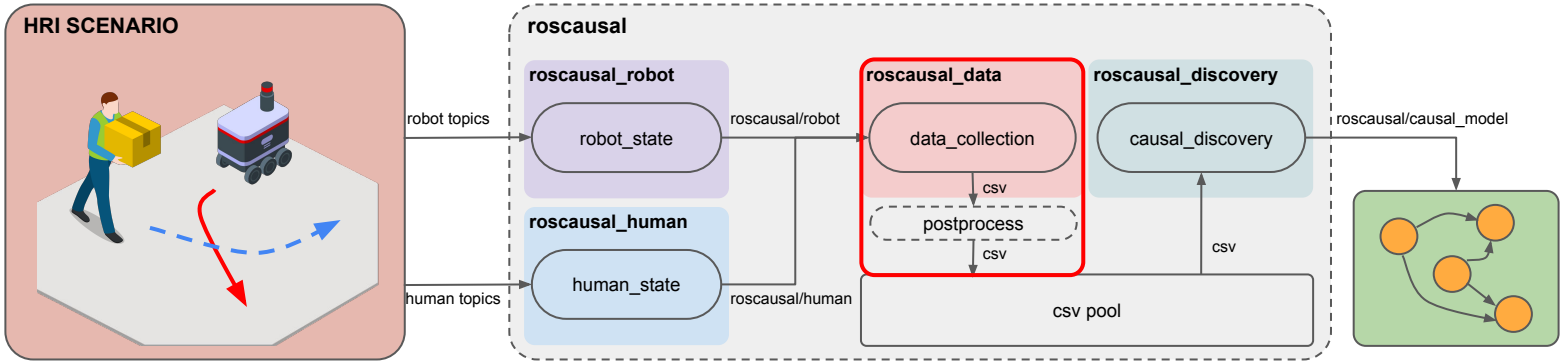
ROS-based Causal Analysis Framework



- ROS-Causal is composed by four different rosnodes:
  - roscausal_robot
  - roscausal_human
  - **roscausal_data**: subscribes to the topics */roscausal/robot* and */roscausal/human* and begins collecting data in a CSV file. Once the desired time-series length (rosparam) is reached, the node provides the option to post-process the data and finally saves the CSV file into a designated folder.
  - roscausal_discovery

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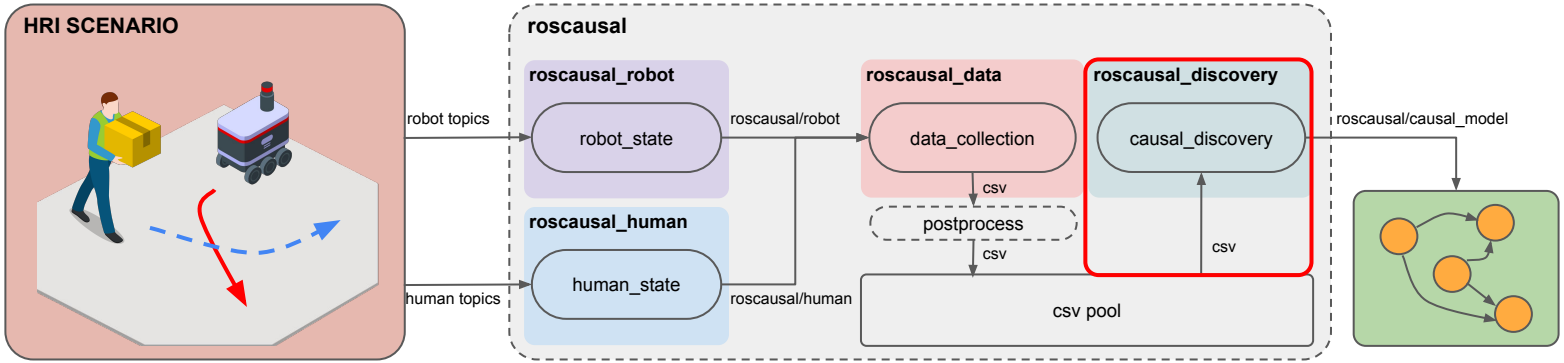
ROS-based Causal Analysis Framework



- ROS-Causal is composed by four different rosnodes:
  - roscausal_robot
  - roscausal_human
  - roscausal_data
  - **roscausal_discovery**: performs causal discovery analysis on the collected data and publishes the result on the *roscausal/causal_model* rostopic. So far, it incorporates two causal discovery methods: PCMCI[2] and its extension, F-PCMCI[3].

[2] Jakob Runge. 2018. Causal network reconstruction from time series: From theoretical assumptions to practical estimation. Chaos: An Interdisciplinary Journal of Nonlinear Science 28, 7 (2018).
[3] Luca Castri, Sariah Mghames, Marc Hanheide, and Nicola Bellotto. 2023. Enhancing Causal Discovery from Robot Sensor Data in Dynamic Scenarios. In 2nd Conference on Causal Learning and Reasoning.

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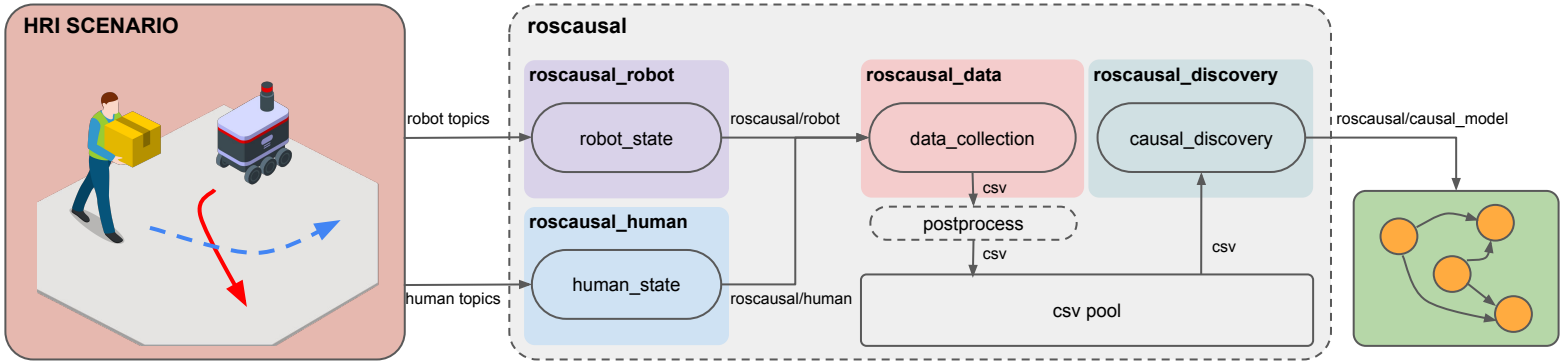
ROS-based Causal Analysis Framework



- ROS-Causal is composed by four different rosnodes:
  - roscausal_robot
  - roscausal_human
  - roscausal_data
  - roscausal_discovery

operate asynchronously, allowing the simultaneous execution of causal analysis on one dataset while continuing the collection of another.

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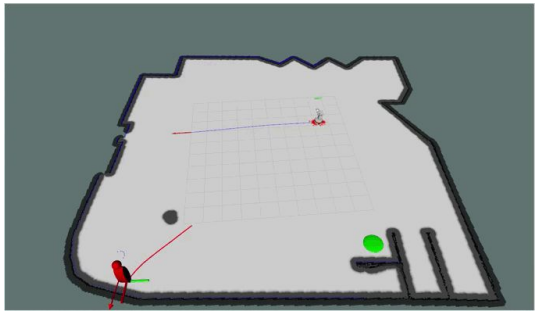
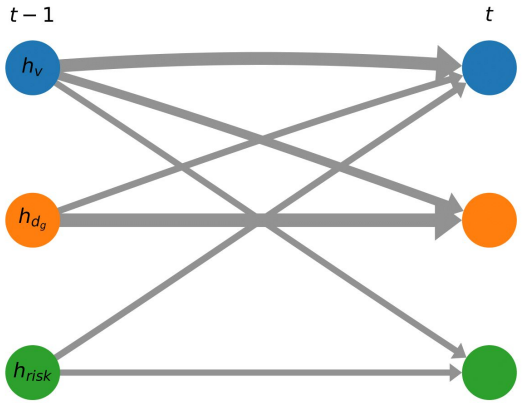
Simulation environment and ROS-Causal Evaluation

- ROS-Causal_HRISim is an ad-hoc simulator for HRIs that includes: ROS-Causal, TIAGo robot[2], pedestrians (teleoperated and autonomous) modelled by pedsim_ros[3];
- To evaluate ROS-Causal, we designed a HRI scenario, inspired by [4], that involves a TIAGo robot and a teleoperated person. The considered variables are the following:
  - h_v - human velocity;
  - h_{dg} - distance between the human and his target position (●);
  - h_{risk} - risk of collision with the robot.
- the expected causal links in this scenario are as follows:
  - $h_v \rightarrow h_{dg}$: inverse relationship;
  - $h_{d_g} \rightarrow h_v \leftarrow h_{risk}$: velocity direct function of the distance, but it is also affected by the risk of collision;
  - $h_v \rightarrow h_{risk}$: risk depends on the velocity, as explained in [4].





[2]https://pal-robotics.com/robots/tiago/

[3]https://github.com/srl-freiburg/pedsim_ros

[4] Luca Castri, Sariah Mghames, Marc Hanheide, and Nicola Bellotto. 2022. Causal discovery of dynamic models for predicting human spatial interactions. In International Conference on Social Robotics. Springer, 154–164.

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Conclusion and Future Work

- In this work, we proposed:
  - **ROS-Causal**, a ROS-based causal analysis framework for human-robot interactions applications that enables onboard data collection and causal discovery, allowing robots to concurrently reconstruct the causal model while collecting data for future causal analysis;
  - **ROS-Causal_HRISim**, an HRI simulator used to facilitate the design of HRI scenarios and to collect observational and interventional data for causal analysis;
- **Future work:**
  - roscausal_robot and roscausal_human can be enhanced to accommodate multiple robots and humans;
  - integration of additional causal discovery methods beyond PCMCI and F-PCMCI. Thanks to the ROS-Causal modular design, this can be easily achieved by introducing new scripts within the dedicated folder for causal discovery methods in the roscausal_discovery node;
  - ROS2 compatibility;
  - introduction of a new block to the pipeline for leveraging and reasoning on the reconstructed causal models, e.g., roscausal_reasoning.

References

[1] Judea Pearl. 2009. Causality. Cambridge University Press.

[2] Jakob Runge. 2018. Causal network reconstruction from time series: From theoretical assumptions to practical estimation. Chaos: An Interdisciplinary Journal of Nonlinear Science 28, 7 (2018).

[3] Luca Castri, Sariah Mghames, Marc Hanheide, and Nicola Bellotto. 2023. Enhancing Causal Discovery from Robot Sensor Data in Dynamic Scenarios. In 2nd Conference on Causal Learning and Reasoning.

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ROS-Causal_HRISim

Thank you

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