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

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

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

DARKO Dynamic Agile Production Robots That Learn and Optimise Knowledge and Operations

Website: ***https://darko-project.eu***
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017274

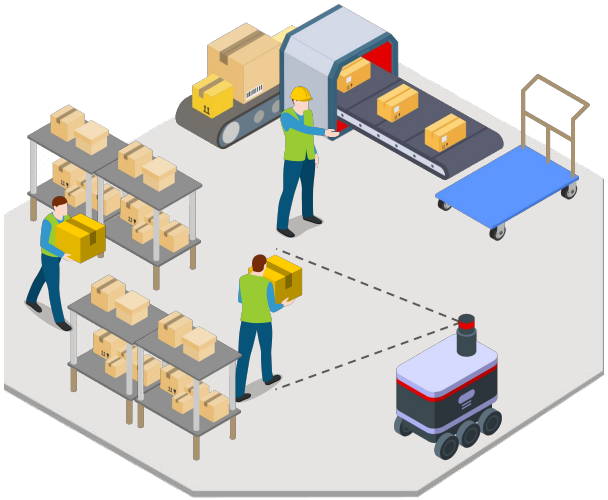
Future Artificial Intelligence Research

Website: ***https://fondazione-fair.it***
PNRR MUR project PE0000013-FAIR

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

*Motivation and Contribution*

- Exploiting robots in activities where the environment is shared with humans ⟹ new approaches for effective HRIs;
- Causal inference can be a key factor in enhancing HRIs;
- Most causal discovery methods for time-series data lack integration with the 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.



PCMCI F-PCMCI
DYNOTEARS TiMINo
VARLiNGAM TCDF tsFCI

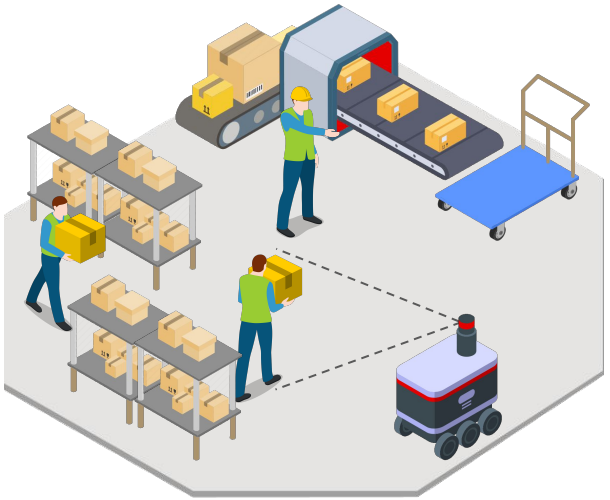
ROS

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

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

*Motivation and Contribution*

- **ROS-Causal** [1]: ROS-Based causal analysis framework for Human-Robot Interaction applications:
  - allows data collection and causal discovery from time-series data directly onboard the robot;
  - uses data from its own sensors;
- Our contributions are:
  - the first runtime creation of a HRSI causal model onboard the robot with its sensors data, via ROS-Causal;
  - an experimental evaluation of the latter in HRSI scenarios, including 15 human participants;
  - a new dataset of human-goal and HRSI trajectories.



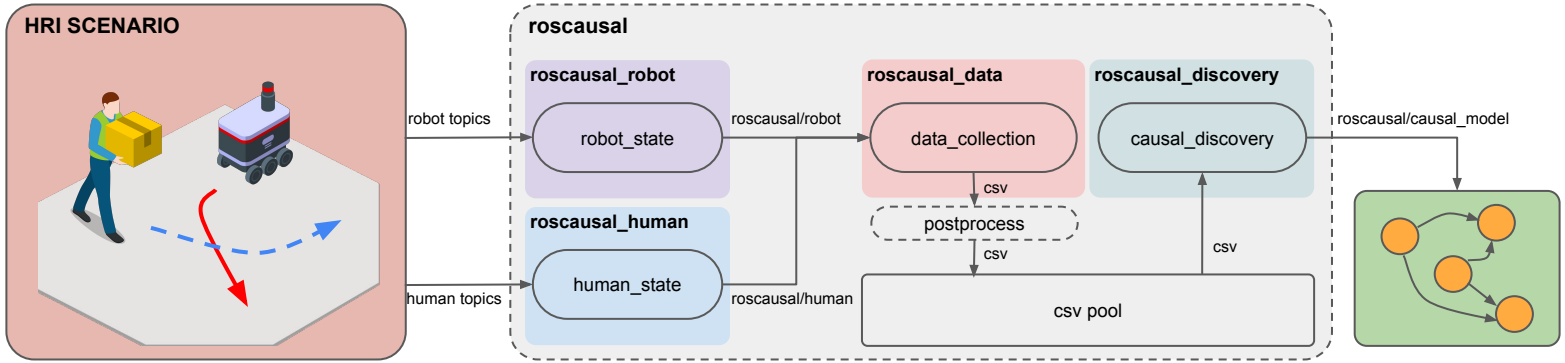
PCMCI F-PCMCI
DYNOTEARS TiMINo
VARLiNGAM TCDF tsFCI

ROS

[1] L. Castri, G. Beraldo, S. Mghames, M. Hanheide and N. Bellotto (2024).
ROS-Causal: A ROS-based Causal Analysis Framework for Human-Robot Interaction Applications,
Workshop on Causal Learning for Human-Robot Interaction (Causal-HRI), ACM/IEEE International Conference on Human-Robot Interaction (HRI).

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

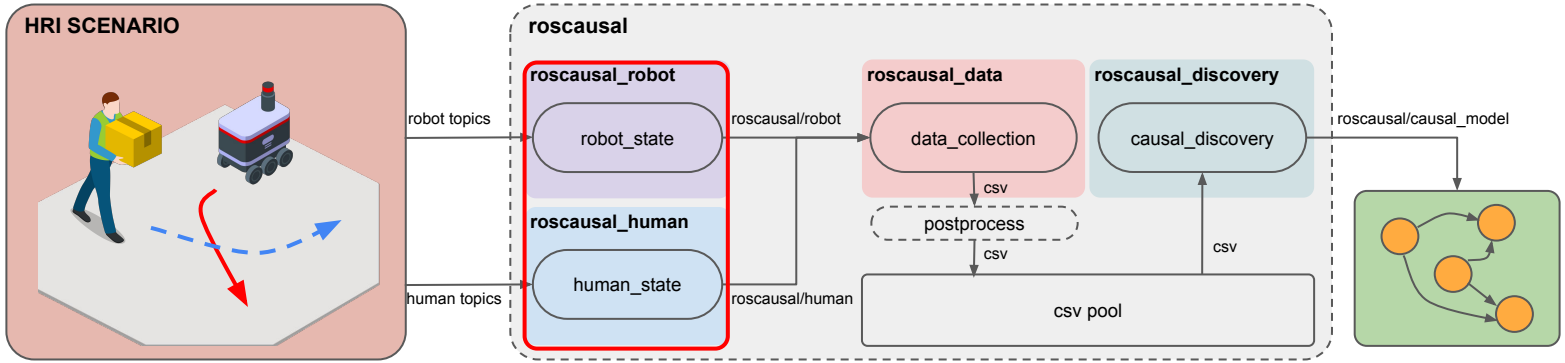
*ROS-Causal*




- 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

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

*ROS-Causal*

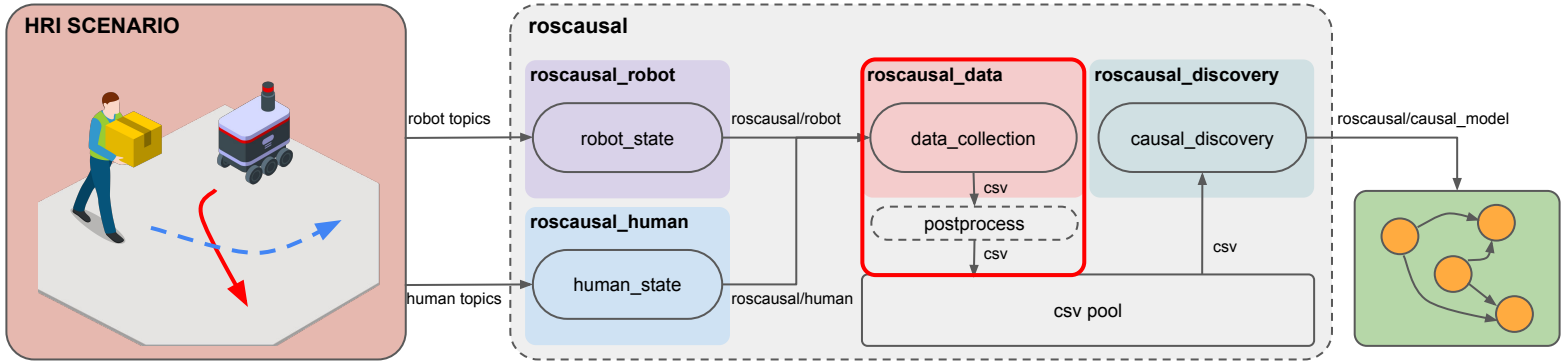



ROS-Causal

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

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

*ROS-Causal*

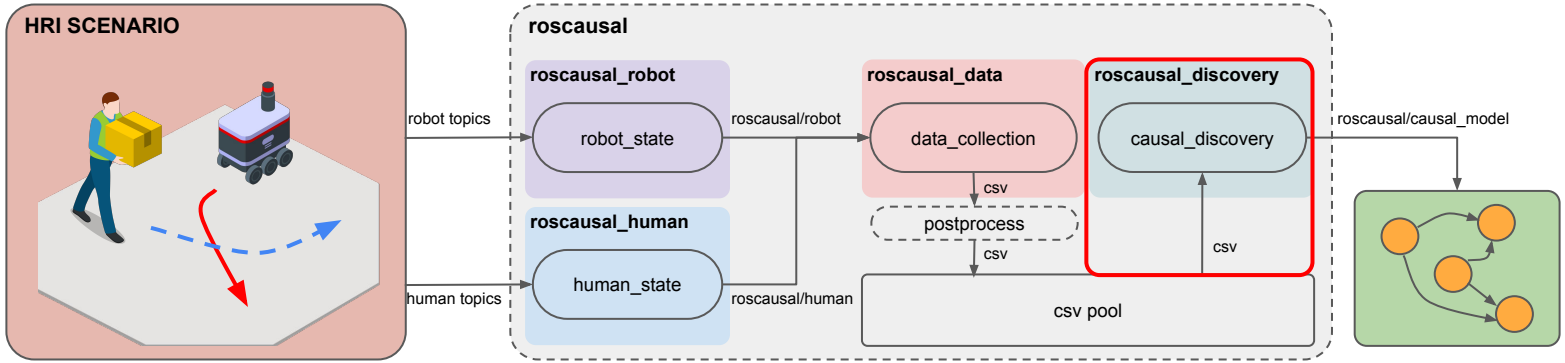



ROS-Causal

- 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

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

*ROS-Causal*



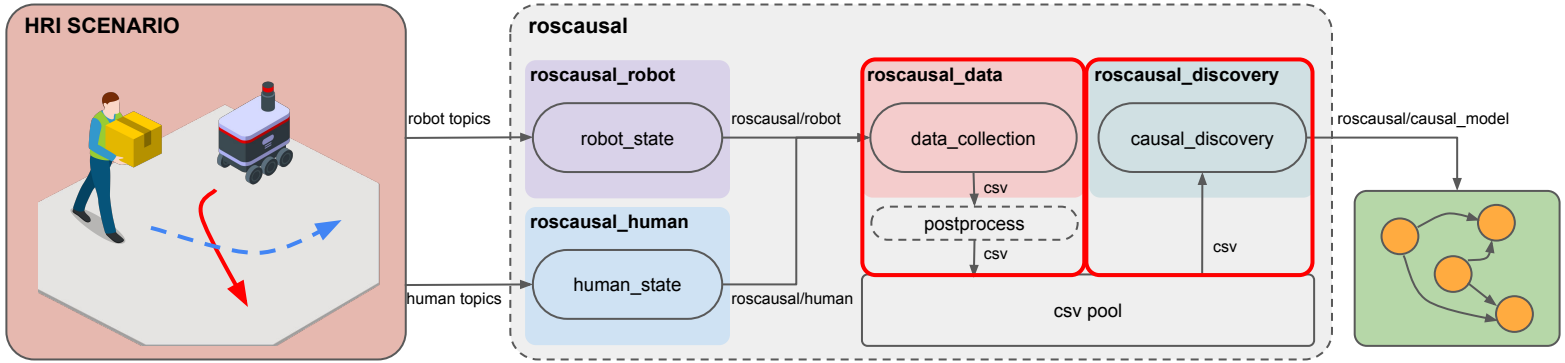

ROS-Causal

- 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] J. 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] L. Castri, S. Mghames, M. Hanheide, and N. Bellotto. 2023. Enhancing Causal Discovery from Robot Sensor Data in Dynamic Scenarios. In 2nd Conference on Causal Learning and Reasoning.

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

*ROS-Causal*




ROS-Causal

- 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 the available dataset while continuing the collection of new ones.

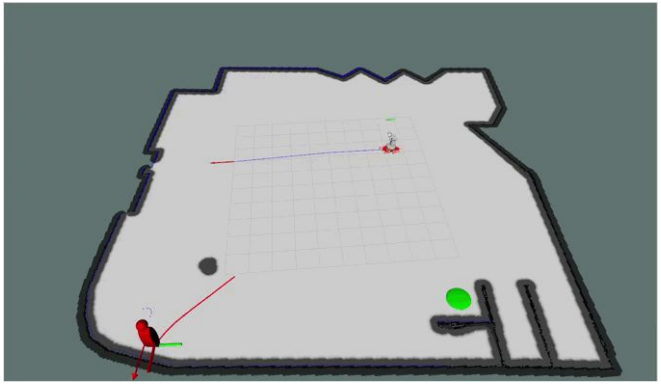
# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

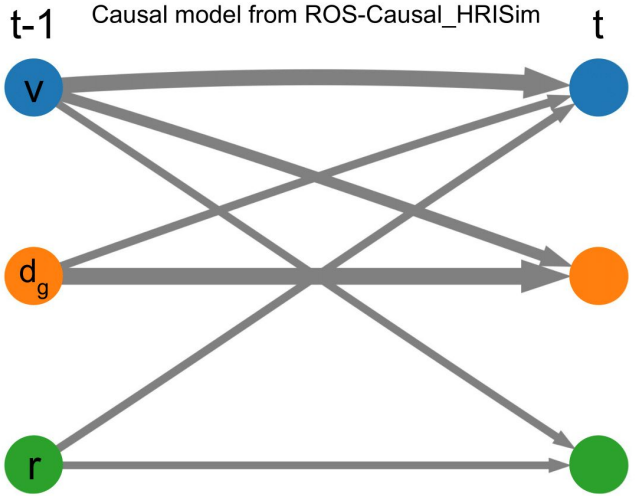
*ROS-Causal Simulation Evaluation*

- ROS-Causal_HRISim – an ad-hoc simulator for HRIs that includes:
  - ROS-Causal
  - TIAGo robot[2]
  - teleoperated and autonomous pedestrians [pedsim_ros[3]]

- ROS-Causal simulation evaluation:
  - HRI scenario [4]: a TIAGo robot and a teleoperated person.
    Considered variables:
    - $v$ human velocity;
    - $d_g$ human - target position distance (●);
    - $r$ risk of collision with the robot.

- the expected causal links in this scenario are as follows:
  - $v \rightarrow d_g$ : inverse relationship;
  - $d_g \rightarrow v \leftarrow r$ : velocity directly depends on the distance, but it is also affected by the risk of collision;
  - $v \rightarrow r$ : 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] L. Castri, S. Mghames, M. Hanheide, and N. Bellotto. 2022. Causal discovery of dynamic models for predicting human spatial interactions. In International Conference on Social Robotics. Springer, 154–164.

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

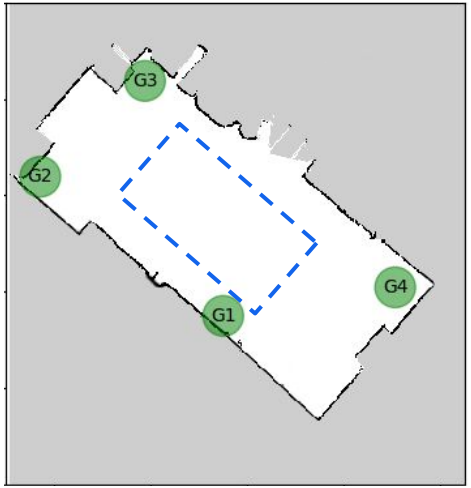
*ROS-Causal Evaluation in Lab Scenario*

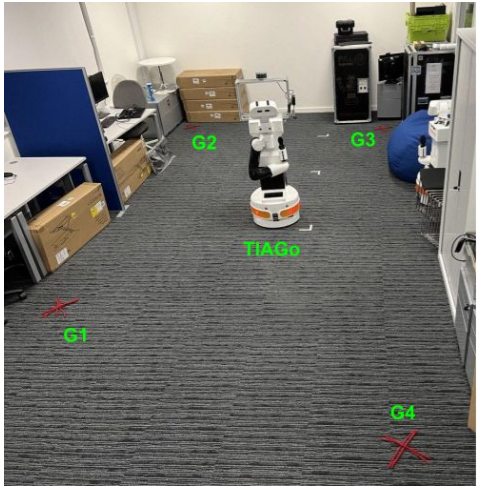
**$R_1$)** Is it feasible to generate causal models onboard the robot via ROS-Causal?

**$R_2$)** If yes, how much data (i.e., time-series length and sampling frequency) is needed to generate accurate causal models?

**$R_3$)** If yes, how much execution time does the generation take?

- Human trajectory tracking: Velodyne VLP-16 3D LiDAR [10 Hz] and the Bayes People Tracker
- laboratory room 5x8.2m




**Participant task**

- four goal positions
- avoiding collisions with the robot

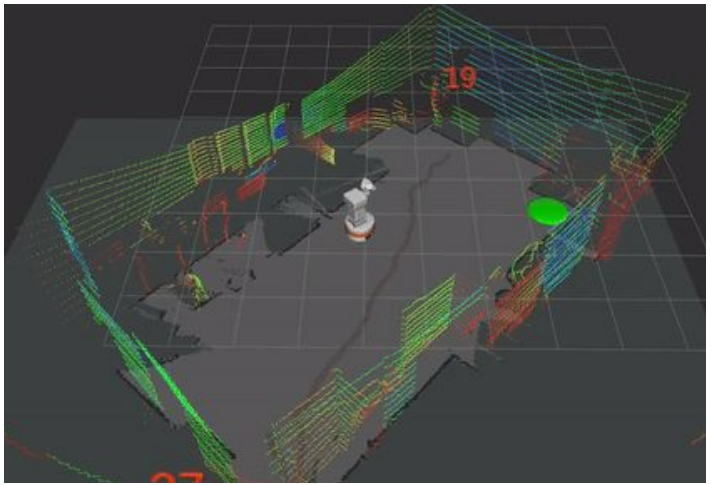
**TIAGo task**

- predefined rectangular path

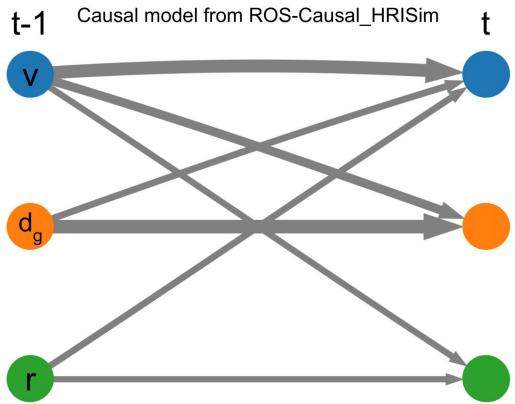
# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

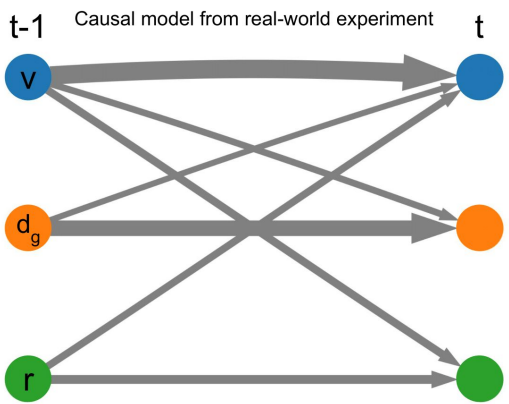
*ROS-Causal Evaluation in Lab Scenario*

- data collection, post-processing and causal discovery via ROS-Causal;
- the causal model structure is consistent with those found in [4] and the simulation experiment.


**$R_1$)** Is it feasible to generate causal models onboard the robot via ROS-Causal? **YES**




[4] L. Castri, S. Mghames, M. Hanheide, and N. Bellotto. 2022. Causal discovery of dynamic models for predicting human spatial interactions. In International Conference on Social Robotics. Springer, 154–164.

# Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios

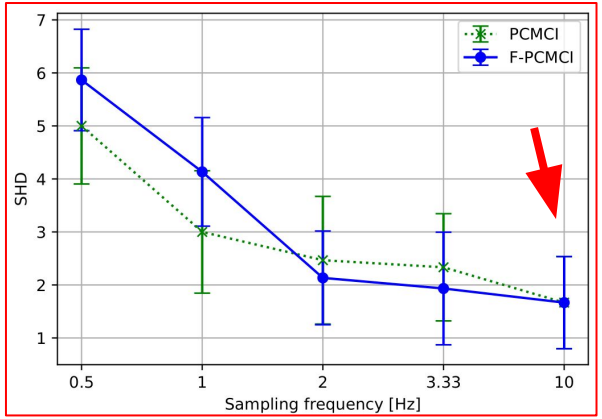
*ROS-Causal Evaluation in Lab Scenario*

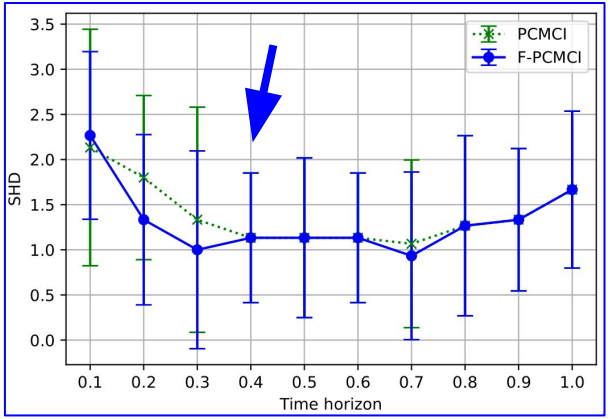
## Sampling frequency analysis

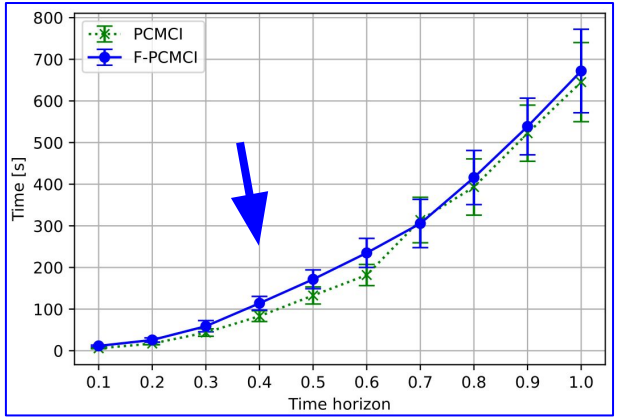
- time-series length: ~5 minutes
- sampling frequencies: from 0.5Hz to 10Hz
- metric: **SHD**

## Time horizon analysis

- time-series length: from 10% to 100% of the full length
- sampling frequency: 10Hz
- metric: **SHD**




**R2)** how much data (time-series length and sampling frequency) is needed to generate accurate causal models?
**R3)** how much execution time does the generation take?

**40% (120s)** length of the time-series recorded at **10Hz**:
best trade-off between accuracy of the causal model and time required to reconstruct it (~100s).

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

*Conclusion and Future Work*

- **Summary**
  - we evaluated the effectiveness of the ROS-Causal framework in modelling human-robot spatial interactions, both in simulated and lab environments
  - we proved feasibility of onboard causal discovery with a real robot
  - we demonstrated how to analyse execution time and data requirements (time-series length and sampling frequency) of a specific scenario for generating accurate causal models
- **Future work**
  - investigate more complex interactions in logistics and similar working environments, where multiple people share the space with the robot.
  - conduct a cause-effect estimation between variables to compare not only the structure of the retrieved causal model but also its actual parameters, such as causal link strengths
  - extend ROS-Causal's capabilities beyond causal discovery, especially to leverage causal models for tasks such as robot planning and real-time interaction prediction.

# References


[1] L. Castri, G. Beraldo, S. Mghames, M. Hanheide and N. Bellotto (2024). **ROS-Causal: A ROS-based Causal Analysis Framework for Human-Robot Interaction Applications**, Workshop on Causal Learning for Human-Robot Interaction (Causal-HRI), ACM/IEEE International Conference on Human-Robot Interaction (HRI).

[2] J. 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] L. Castri, S. Mghames, M. Hanheide, and N. Bellotto. 2023. **Enhancing Causal Discovery from Robot Sensor Data in Dynamic Scenarios**. In 2nd Conference on Causal Learning and Reasoning.

[4] L. Castri, S. Mghames, M. Hanheide, and N. Bellotto. 2022. **Causal discovery of dynamic models for predicting human spatial interactions**. In International Conference on Social Robotics. Springer, 154–164.


**ROS-Causal**

Thank you


DARKO
Dynamic Agile Production Robots That Learn and Optimise Knowledge and Operations

Website: ***https://darko-project.eu***
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017274

Future Artificial Intelligence Research

Website: ***https://fondazione-fair.it***
PNRR MUR project PE0000013-FAIR