Causal Inference for Intelligent Mobile Robots in Dynamic Interaction Settings

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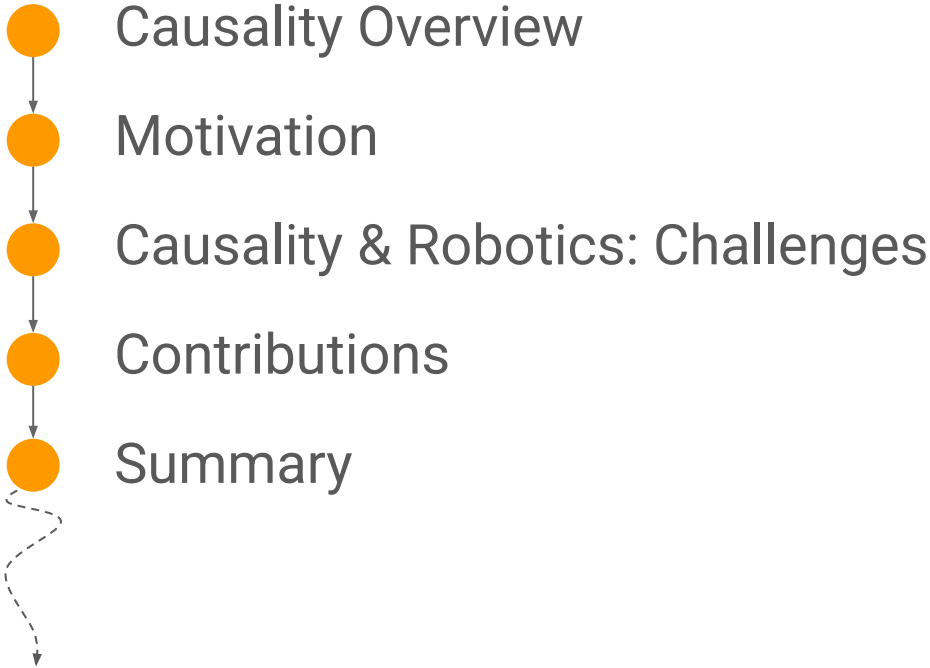
Website: ***https://darko-project.eu***
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017274

Outline

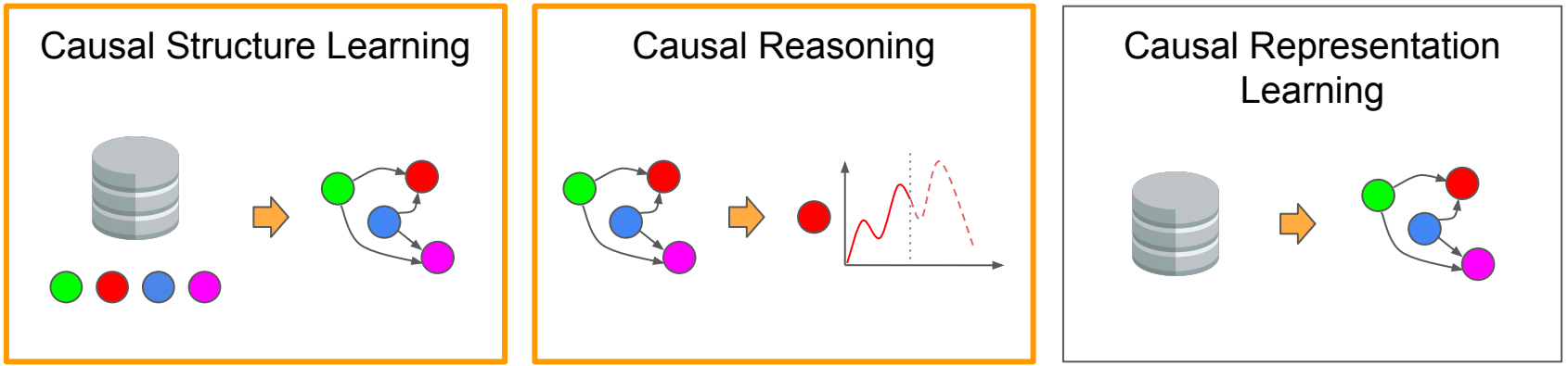

Causality Overview
Motivation
Causality & Robotics: Challenges
Contributions
Summary

Causality Overview

What is it?

> “Science that studies the cause-and-effect relationship between events”
> [Pearl, J., & Mackenzie, D. (2019). The book of why]

How can robots benefit from causality?



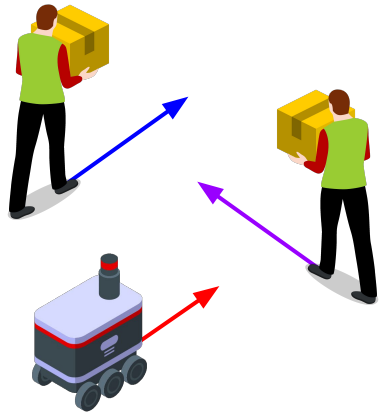
Motivation

Causality applications so far:

- Climate [Runge et al. 2014, 2018, 2019, 2020, Kretschmer et al. 2016, 2017, 2018, …]
- Healthcare [Runge et al. 2015, Saetie et al. 2021, …]
- Machine learning [Schölkopf et al. 2021, Seitzer et al. 2021, …]
- Robotics
  - Imitation learning [Kats et al. 2018, Angelov et al. 2019, 2020]
  - Manipulation [Brawer et al. 2021, Lee et al. 2022, 2023, Cannizzaro et al. 2023a]
  - Autonomous Driving [Howard et al. 2023a,b, 2025]
  - Social HRI [Love et al. 2024a,b]
  - Others [Cao et al. 2021, Cannizzaro et al. 2023b]

  - Causality for modelling human spatial behaviour and robot interactions?

    [Mahata et al. 2017, Vasconez et al. 2019, Jahanmahin et al. 2022, Mukherjee et al. 2022, Dahiya et al. 2023] } Causality not employed



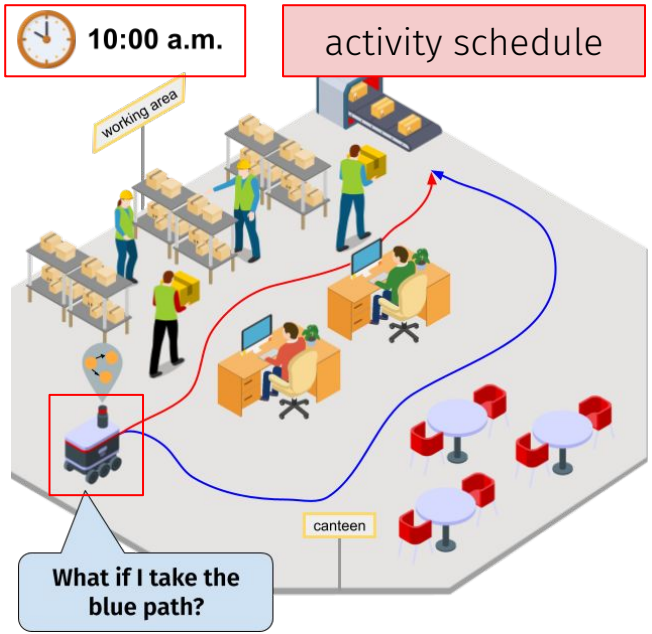
Motivation

Why do we need causal models?

Traditional modelling approaches for human spatial behaviours often ignore the factors that influence them

Having a causal model of human spatial behaviours could enable robots to reason as follows:

- “what happens if I go this way?”



Motivation

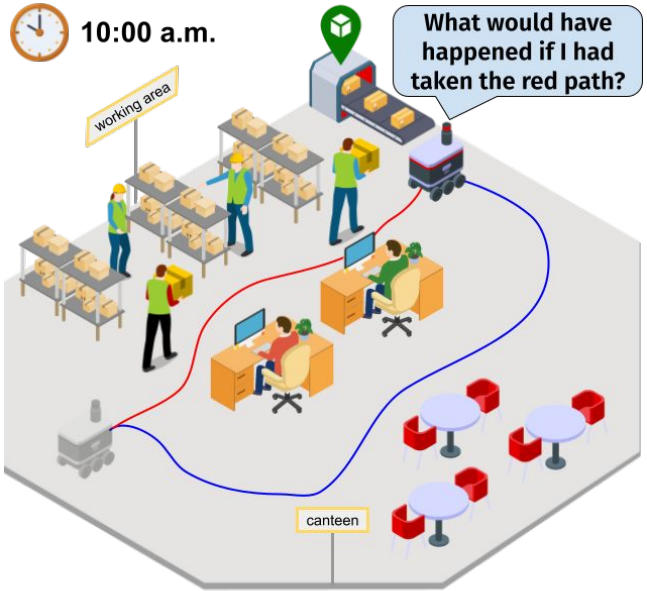
Why do we need causal models?

Traditional modelling approaches for human spatial behaviours often ignore the factors that influence them

Having a causal model of human spatial behaviours could enable robots to reason as follows:

- “what happens if I go this way?”
- “what would have happened if I had gone another way?”

➔ deeper understanding of the scenario
➔ decision-making and forecasting



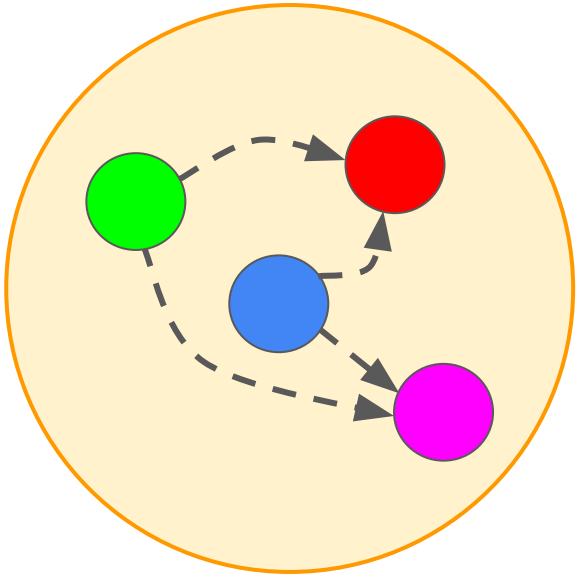
Causality & Robotics: Challenges

Challenge

- Limited resources and real-time demands in mobile robots

Research Question 1:

➔ Is time-series causal discovery feasible for mobile robots in human-shared environments?



Causality & Robotics: Challenges

Challenge

- Causal discovery from time-series uses only observations
- Robots cannot use their embodiment to support causal discovery through interventions

Research Question 2:

➔ Can causal discovery integrate observational and interventional time-series?

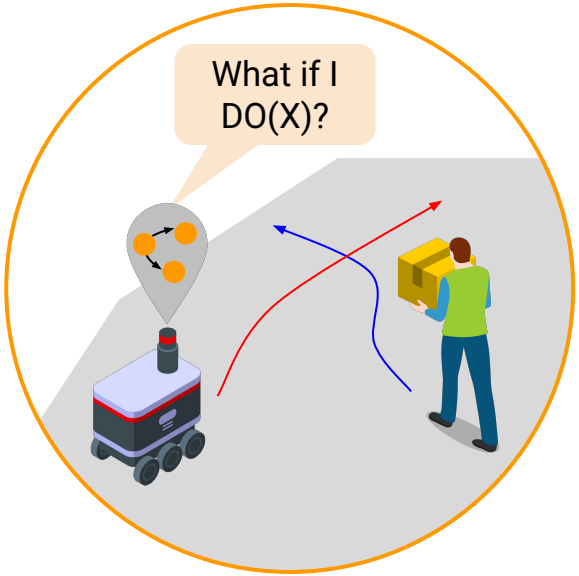
Causality & Robotics: Challenges

Challenge

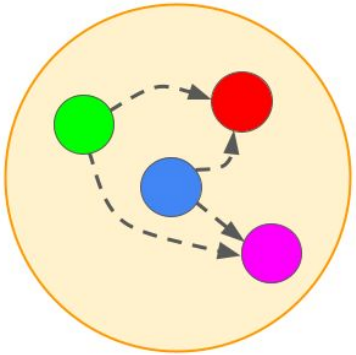
- Causal discovery not integrated into ROS
- No causal reasoning in decision-making

Research Question 3:

➔ Can robots autonomously reconstruct and use causal models to enhance decision-making and interactions in human-shared spaces?

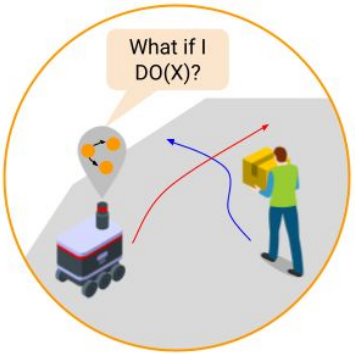


Contributions



Fast and accurate causal discovery algorithm for time-series

Observation and intervention-based causal discovery algorithm for time-series



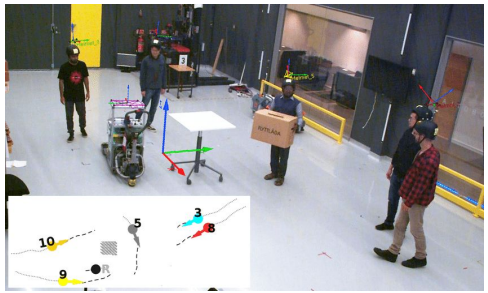
Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Contributions

Fast and accurate causal discovery algorithm for time-series

Is time-series causal discovery feasible for mobile robots in human-shared environments?

THÖR [Rudenko et al. 2020]

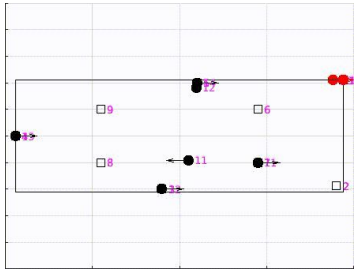


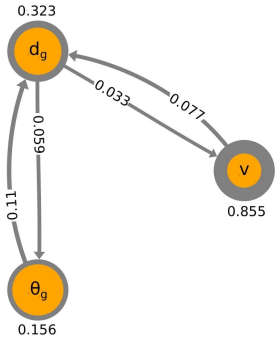
ATC [Brscic et al. 2013]

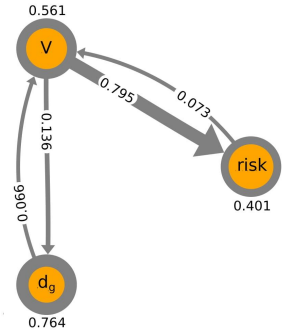
- PCMCI [Runge et al. 2019]

single-agent

multi-agent







Limitation: PCMCI execution time

➔ We need a fast causal discovery method

Contributions

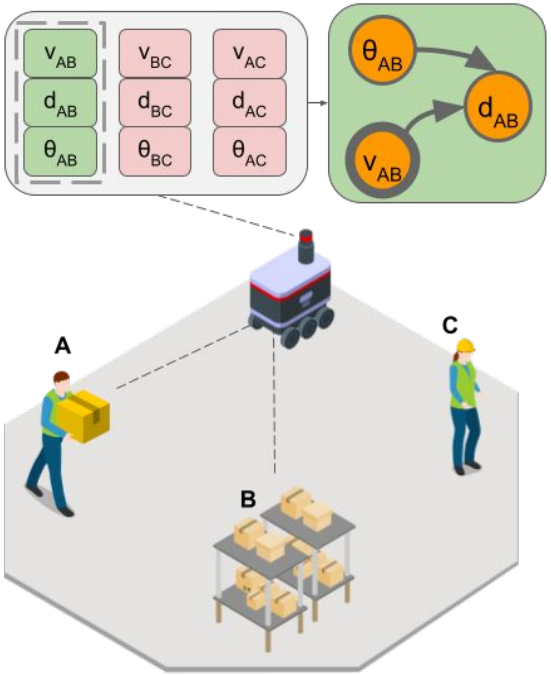
Fast and accurate causal discovery algorithm for time-series

Is it possible to improve the causal discovery process?

- PCMCI computational complexity

$$\mathcal{O}(N^3\tau_{\max}^2 + N^2\tau_{\max})$$

- Are all robot-observed variables useful?



GOAL

- Build an all-in-one solution to select key variables and reconstruct a causal model

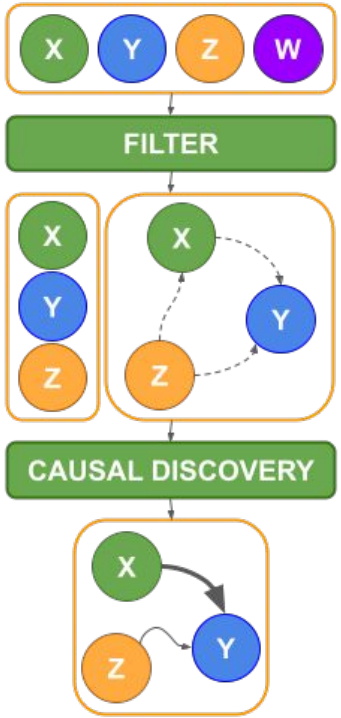
Contributions

Fast and accurate causal discovery algorithm for time-series

Is it possible to improve the causal discovery process?

Filtered-PCMCI (F-PCMCI)

1. predefined set of variables
2. remove irrelevant variables using transfer entropy
3. build hypothetical causal structure from reduced set
4. run PCMCI on hypothetical model



→ **Faster** and **more accurate** causal discovery

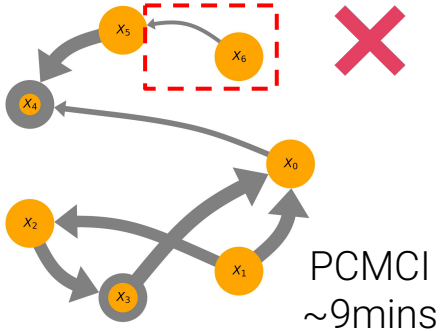
Contributions

Fast and accurate causal discovery algorithm for time-series

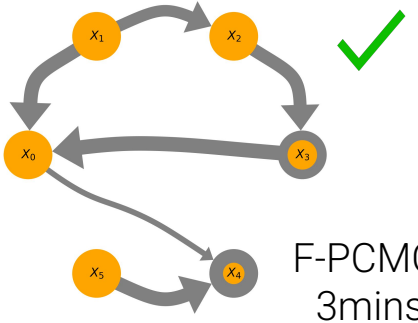
Is it possible to improve the causal discovery process?

Toy problem

$$
\begin{cases}
x_0(t) = 2x_1(t-1) + 3x_3(t-1) + \eta_0 \\
x_1(t) = \eta_1 \\
x_2(t) = 1.1x_1(t-1)^2 + \eta_2 \\
x_3(t) = x_3(t-1) \cdot x_2(t-1) + \eta_3 \\
x_4(t) = x_4(t-1) + x_5(t-1) \cdot x_0(t-1) \\
x_5(t) = \eta_5 \\
x_6(t) = \eta_6 \leftarrow \text{isolated}
\end{cases}
$$

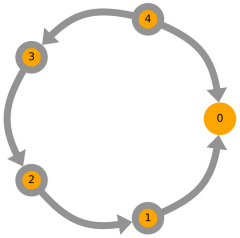


PCMCI
~9mins

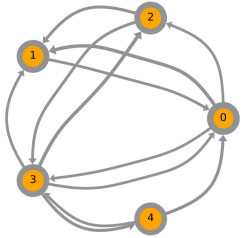


F-PCMCI
3mins

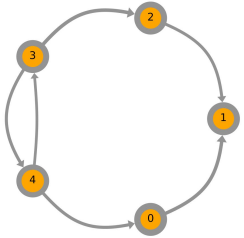
fMRI data [Smith et al. 2011]



GT



PCMCI



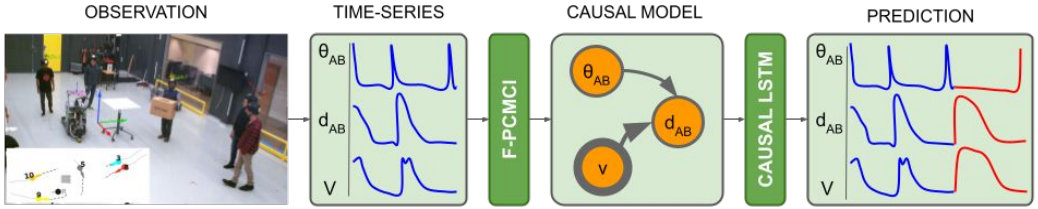
F-PCMCI

	SHD	F1-Score	Time
PCMCI	8	0.69	90'50"
F-PCMCI	**4**	**0.80**	**38'52"**

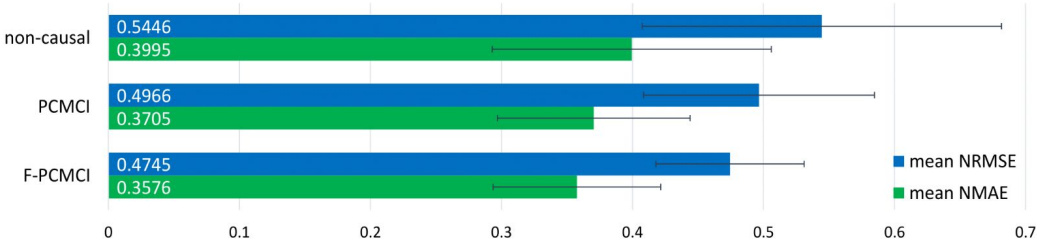
Contributions

Fast and accurate causal discovery algorithm for time-series

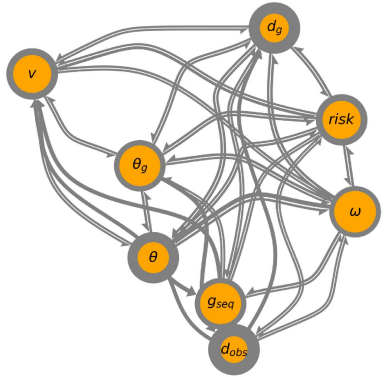
Is it possible to improve the causal discovery process?



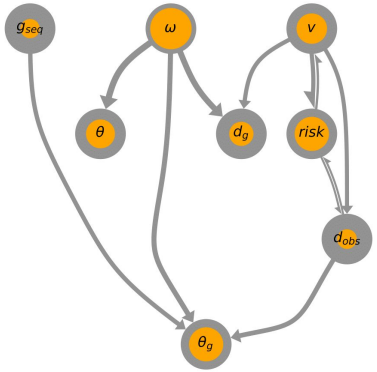
- No ground-truth causal model
- Prediction accuracy used to evaluate causal models



PCMCI ~80mins



F-PCMCI ~18mins



Contributions

Fast and accurate causal discovery algorithm for time-series

Summing up

- Causal discovery is feasible in dynamic human-shared scenarios
- F-PCMCI for fast and accurate causal discovery

Research outcomes

- Castri et al. “Causal discovery of dynamic models for predicting human spatial interactions,” in International Conference on Social Robotics, 2022.
- Castri et al. “Enhancing causal discovery from robot sensor data in dynamic scenarios,” in Conference on Causal Learning and Reasoning, 2023.

CausalFlow
A Unified Framework for Causality in Time-Series

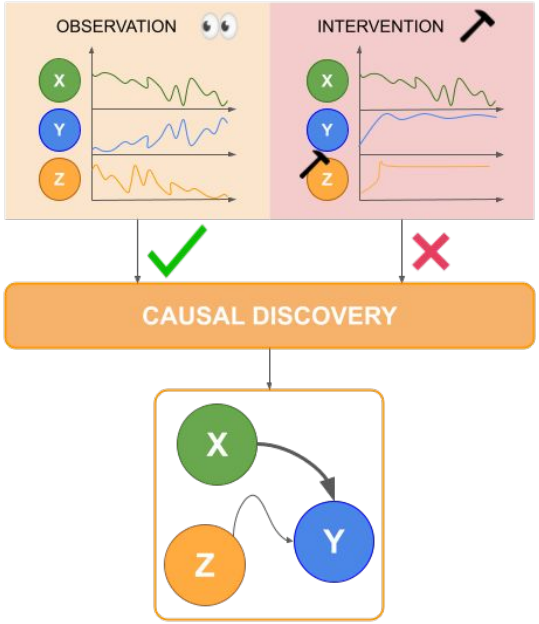
Main limitation: Time-series causal discovery uses only observations. Can interventions help?

Contributions

Observation and intervention-based causal discovery algorithm for time-series

Can causal discovery integrate observational and interventional time-series?

- Observational data alone are often insufficient to identify the correct causal model
- Time-series methods do not integrate interventional data



GOAL

- First causal discovery method for time-series that uses both observational and interventional data

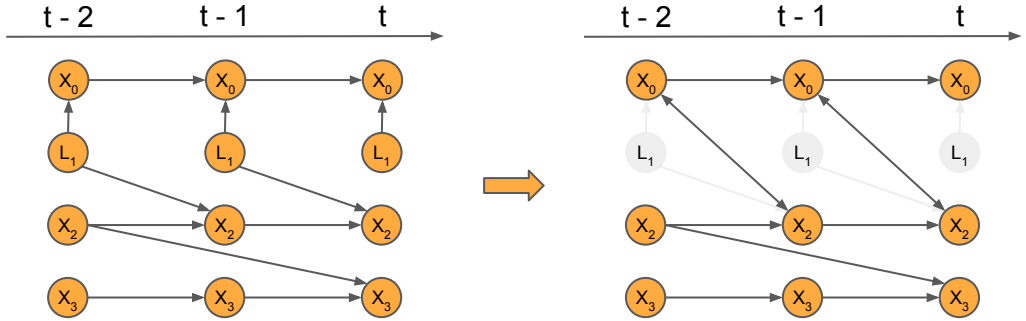
Contributions

Observation and intervention-based causal discovery algorithm for time-series

Can causal discovery integrate observational and interventional time-series?

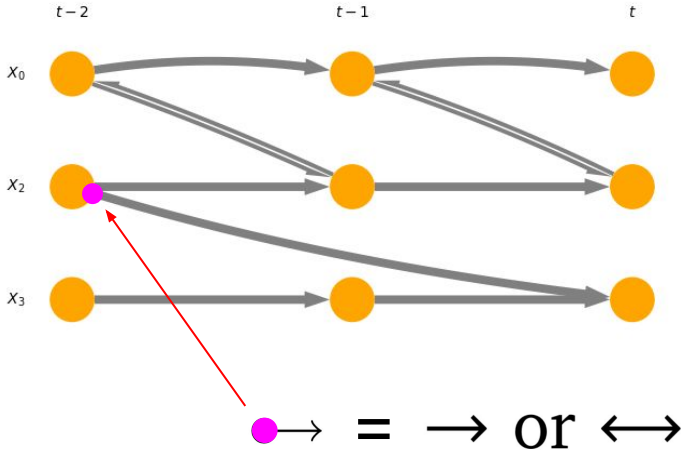
$$\begin{cases} X_0(t) = 0.9X_0(t-1) + 0.6X_1(t) + \eta_0 \\ L_1(t) = \eta_1 \\ X_2(t) = 0.9X_2(t-1) + 0.4X_1(t-1) + \eta_2 \\ X_3(t) = 0.9X_3(t-1) - 0.5X_2(t-2) + \eta_3 \end{cases}$$

LATENT



LPCMCI [Gerhardus et al. 2020]

- based on FCI
- handles latent confounders



Contributions

Observation and intervention-based causal discovery algorithm for time-series

Can causal discovery integrate observational and interventional time-series?

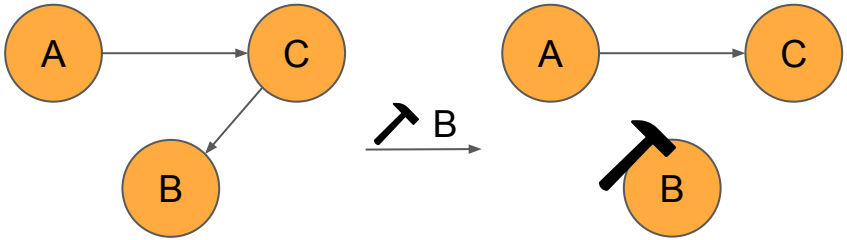
🔨 CAnDOIT

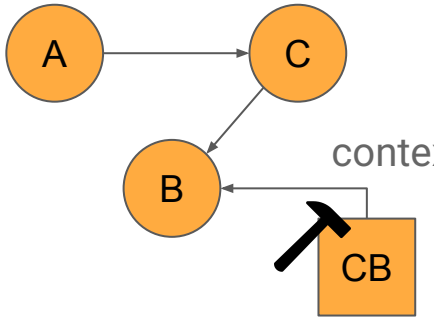
CAusal **D**iscovery with **O**bservational 👀 and **I**nterventional 🔨 data from **T**ime-series

HARD INTERVENTION

- observation: use B's parents
- intervention: remove all inputs to B

How to build this into causal discovery?





context variables to inject interventional data

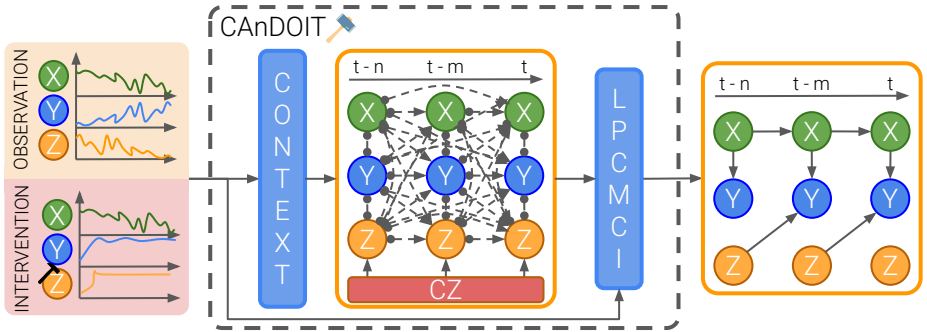
[Mooij et al. 2020]

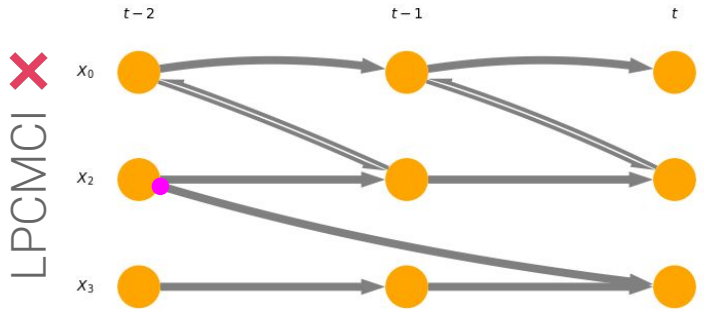
Contributions

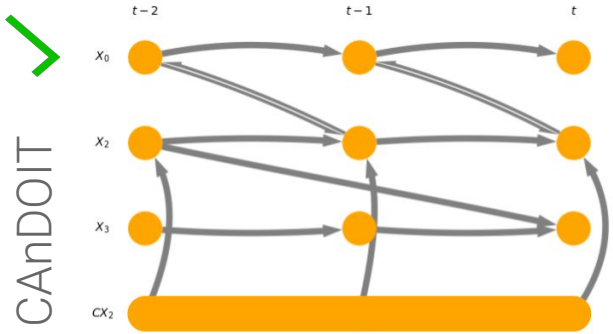
Observation and intervention-based causal discovery algorithm for time-series

Can causal discovery integrate observational and interventional time-series?

$$\begin{cases} X_0(t) = 0.9X_0(t-1) + 0.6X_1(t) + \eta_0 \\ L_1(t) = \eta_1 \\ X_2(t) = 0.9X_2(t-1) + 0.4X_1(t-1) + \eta_2 \\ X_3(t) = 0.9X_3(t-1) - 0.5X_2(t-2) + \eta_3 \end{cases}$$







Contributions

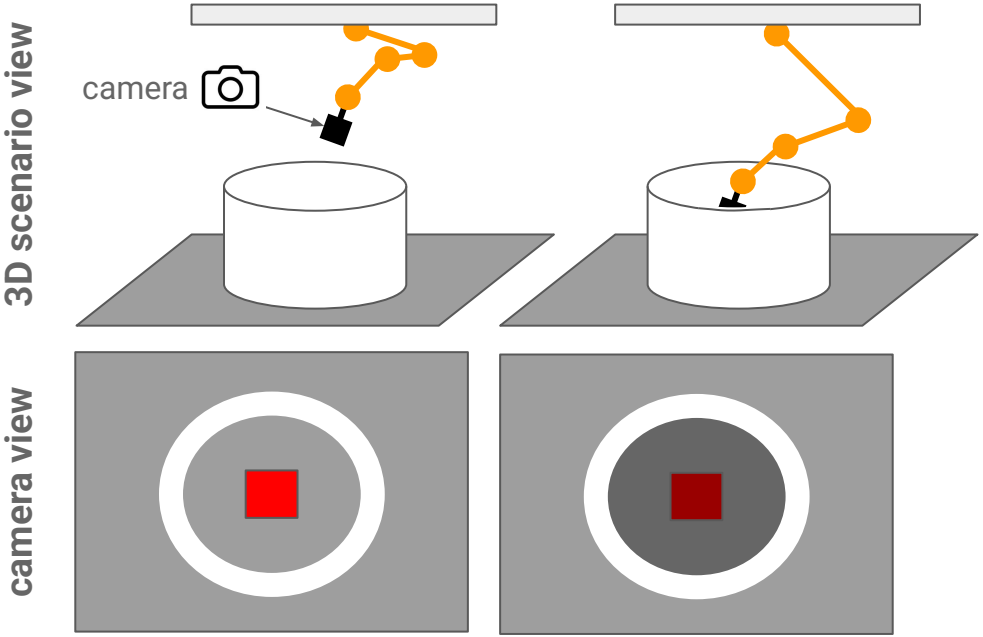
Observation and intervention-based causal discovery algorithm for time-series

Can causal discovery integrate observational and interventional time-series?

$$\begin{cases} F_c(t) = b(H(t-1)) \\ C_c(t) = b(H(t-1), v(t-1), d_c(t-1)) \end{cases}$$

$$b = K_h \frac{H}{H_{max}} + K_v \left(1 - \frac{v}{v_{max}}\right) + K_d \frac{d_c}{d_{c_{max}}}$$

- Floor and cube colours' brightness influenced by:
  - camera height
  - camera velocity
  - camera distance to the cube



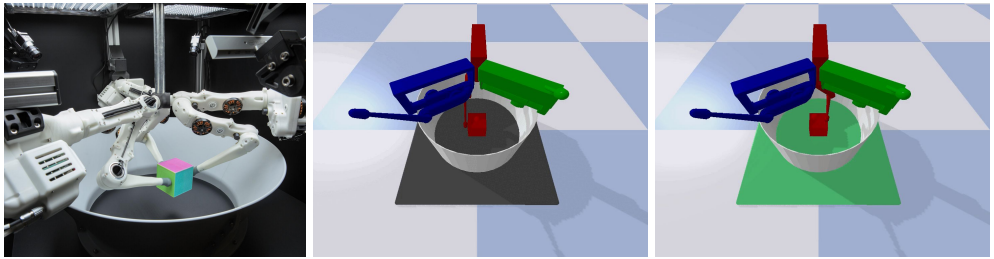
Contributions

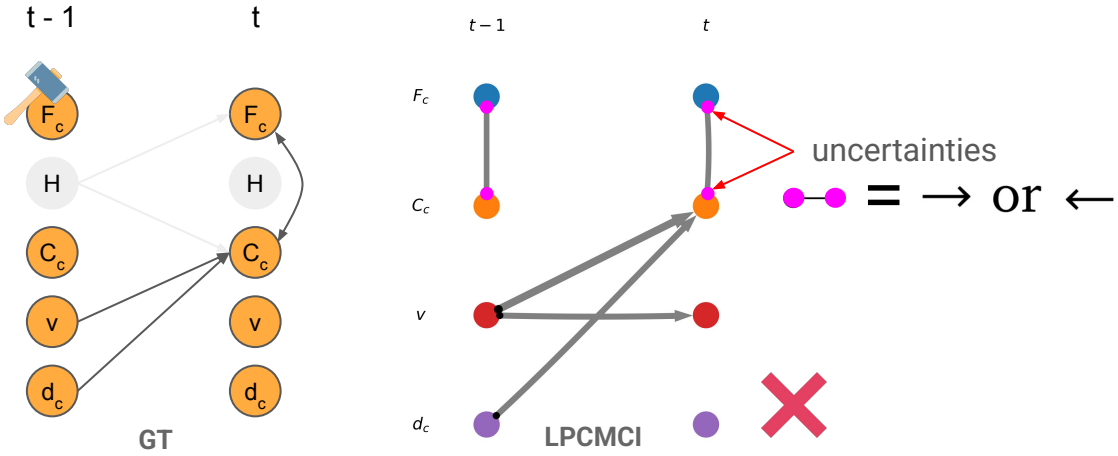
Observation and intervention-based causal discovery algorithm for time-series

Can causal discovery integrate observational and interventional time-series?

[Ahmed et al. 2021]

$$\begin{cases} F_c(t) = b(H(t-1)) \\ C_c(t) = b(H(t-1), v(t-1), d_c(t-1)) \end{cases}$$





Contributions

Observation and intervention-based causal discovery algorithm for time-series

Summing up

- First observation and intervention-based causal discovery method from time-series

Research outcomes

- Castri et al. “CAnDOIT: Causal Discovery with Observational and Interventional Data from Time-Series”, Advanced Intelligent Systems, 2024.

causalFlow
A Unified Framework for Causality in Time-Series

Main limitation:

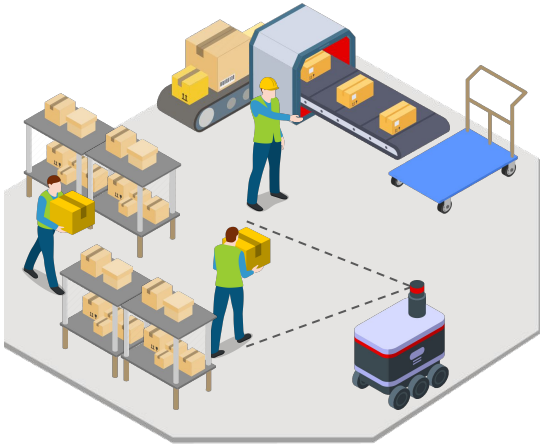
Causal discovery for robots: data collection + offline discovery process. ROS integration?

Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots autonomously reconstruct causal models?

- Causal discovery methods lack an integration with ROS
  - cannot run directly on robots
  - requires data collection + offline analysis
  - causal models not usable in real-time



PCMCI F-PCMCI
DYNOTEARS TiMINo
VARLiNGAM TCDF tsFCI

ROS

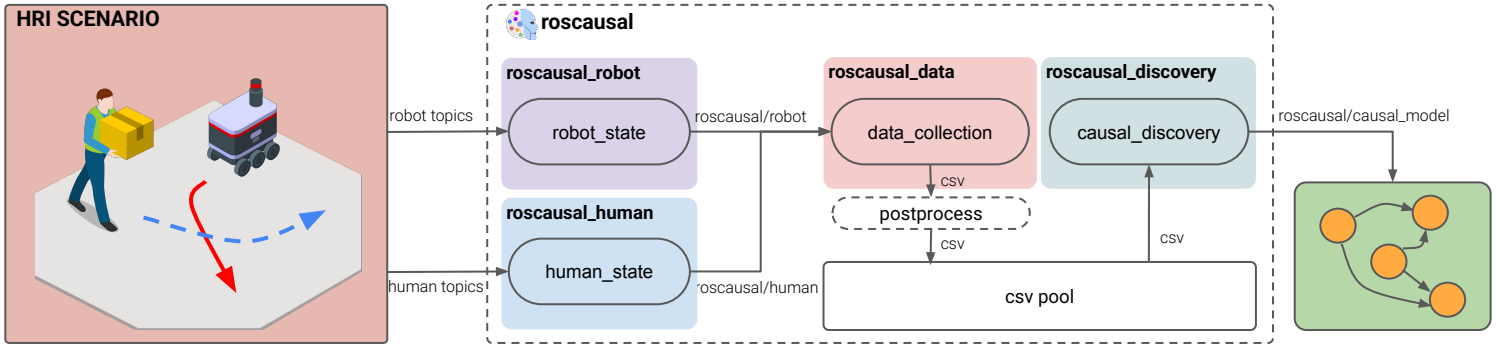
GOAL

- First ROS-based causal analysis framework

Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots autonomously reconstruct causal models?

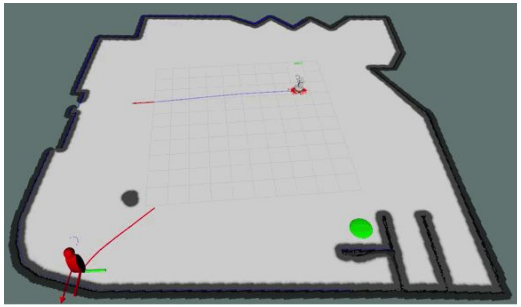


- ROS-Causal is composed by four different rosnodes:
  - roscausal_robot
  - roscausal_human
  - roscausal_data
  - roscausal_discovery

Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots autonomously reconstruct causal models?



- **ROS-Causal_HRISim**
  - TIAGo robot
  - teleoperated and autonomous pedestrians

Multi-agent scenario

variables

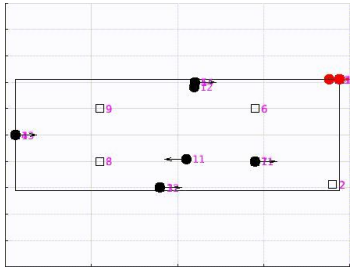
$d_g, v, risk$

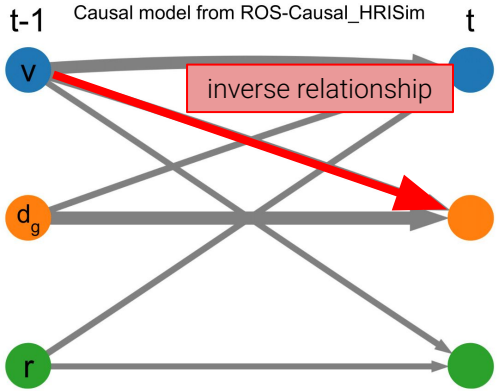
expected cause-effect relationships

$d_g = f(d_g, v)$

$v = f(v, d_g, risk)$

$risk = f(risk, v)$

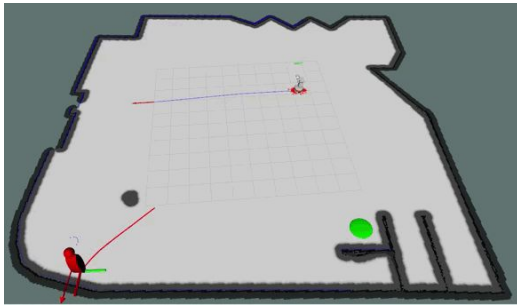




Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots autonomously reconstruct causal models?



- **ROS-Causal_HRISim**
  - TIAGo robot
  - teleoperated and autonomous pedestrians

Multi-agent scenario

variables

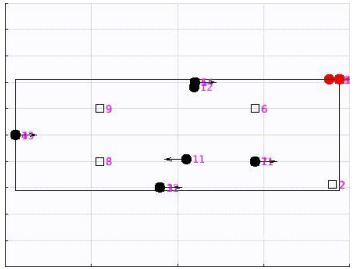
$d_g, v, risk$

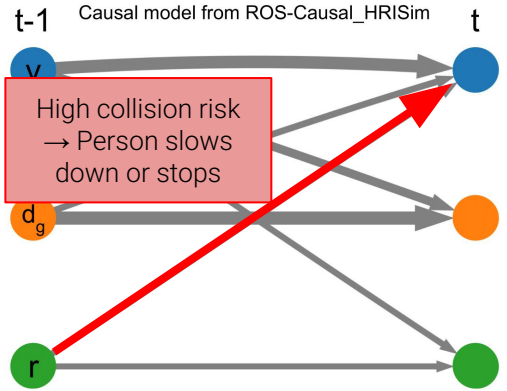
expected cause-effect relationships

$d_g = f(d_g, v)$

$v = f(v, d_g, risk)$

$risk = f(risk, v)$





Contributions

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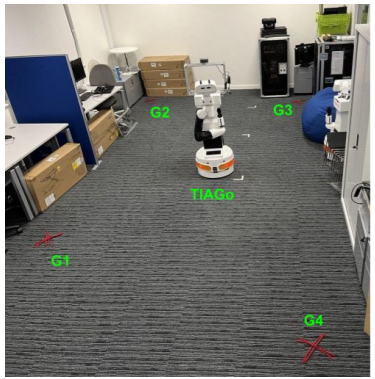
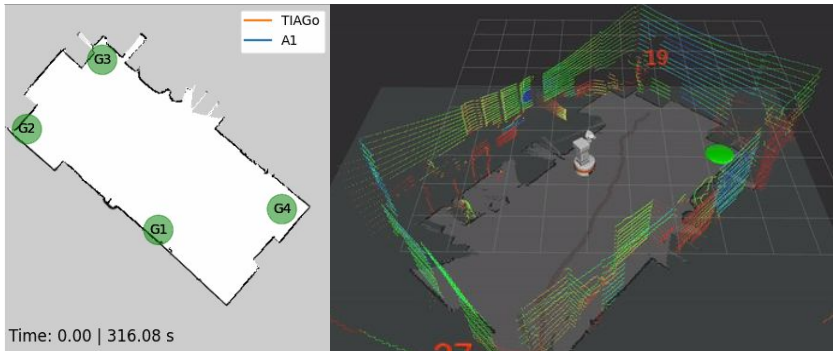
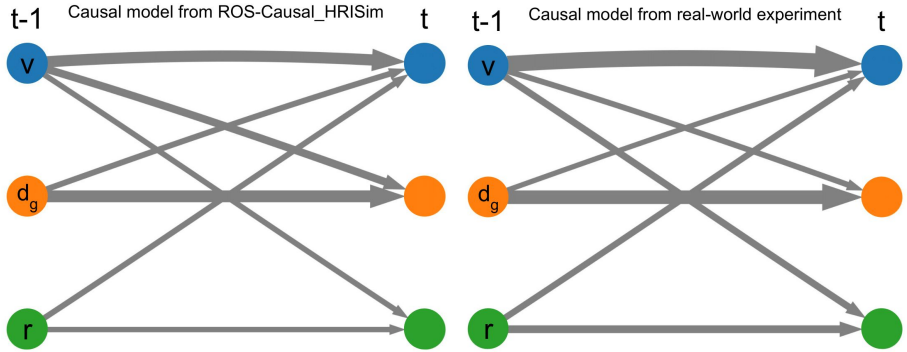


- TIAGo task:
  - predefined rectangular path
- Participant task
  - four goal positions
  - avoid the robot





Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Summing up

- Generate causal models directly robot onboard using data from its own sensors

Research outcomes

- Castri et al. “Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios,” in IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2024.
- Castri et al. “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), 2024.

ROS-Causal

Main limitation: Causal models are discovered. Can the robot actually use them?

Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots use causal models to enhance decisions and interactions in human-shared spaces?

- Human-aware navigation
  - relies on predictive models of human motion
  - ignores contextual factors
- Potential safety and efficiency issues

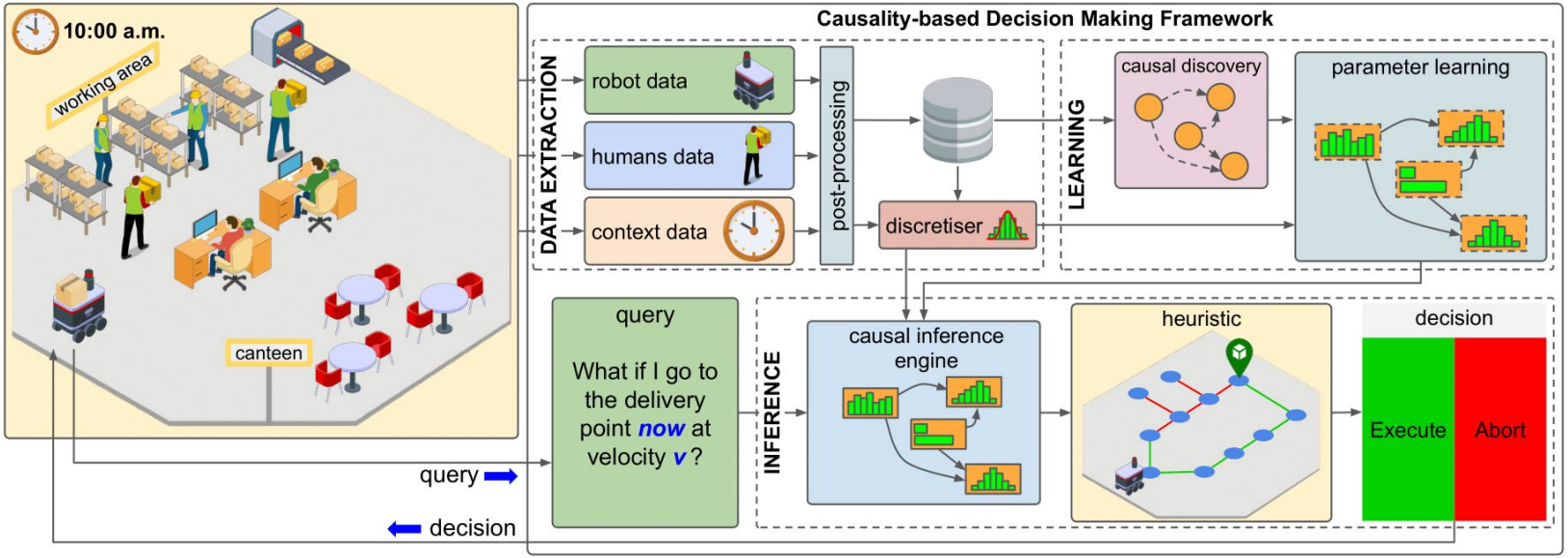
GOAL

- Causality-enhanced decision-making framework

Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots use causal models to enhance decisions and interactions in human-shared spaces?



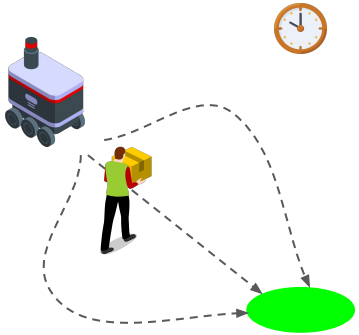
- ➔ Will the robot have enough battery to complete the task?
- ➔ Will the robot get stuck in a crowd, potentially compromising human safety?

Contributions

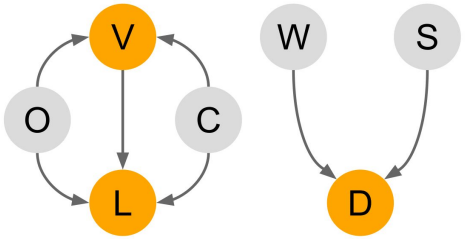
Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots use causal models to enhance decisions and interactions in human-shared spaces?

Robot Task



"What if I go to ● now at velocity v?"



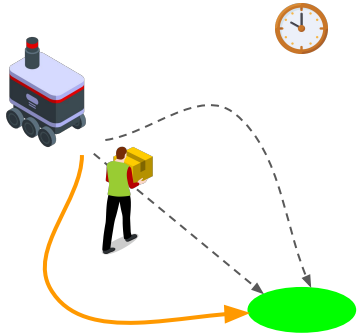
system variables	context factors
V: robot velocity	O: static obstacle
L: battery level change	C: charging status
D: people density	W: waypoint
	S: time slot

$$\hat{L} = \mathbb{E}[L \mid do(V = v), C = c]$$

$$\hat{D} = \mathbb{E}[D \mid do(S = s), W = w] \quad \forall w \in \Omega$$

$$h(w_i) = \sum_{i=1}^{n-1} \left(\lambda_D \cdot \delta(w_i, w_{i+1}) + \lambda_D \cdot \hat{D}(w_i) + \lambda_L \cdot |\hat{L}(w_i, w_{i+1})| \right)$$

Safety and efficiency take priority over distance



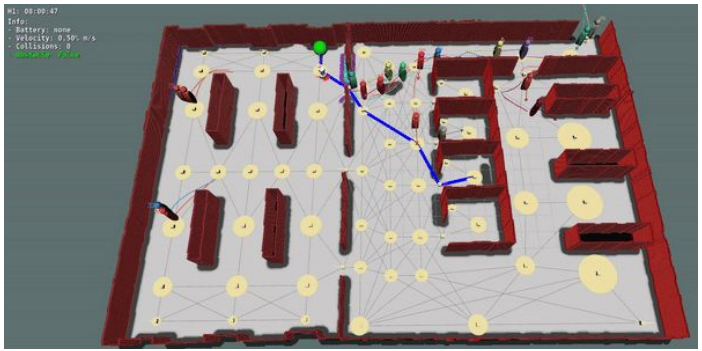
Contributions

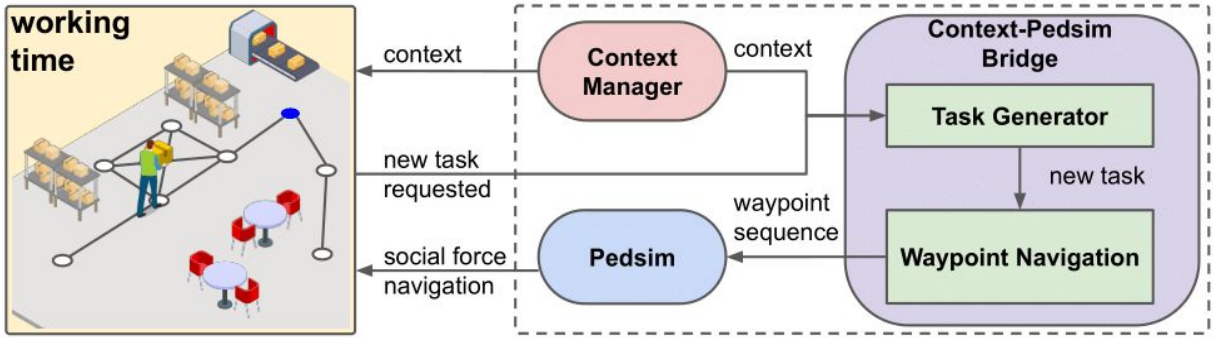
Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots use causal models to enhance decisions and interactions in human-shared spaces?

PeopleFlow

- context-sensitive humans and robot behaviours in a warehouse setting
- TIAGo robot and autonomous pedestrians

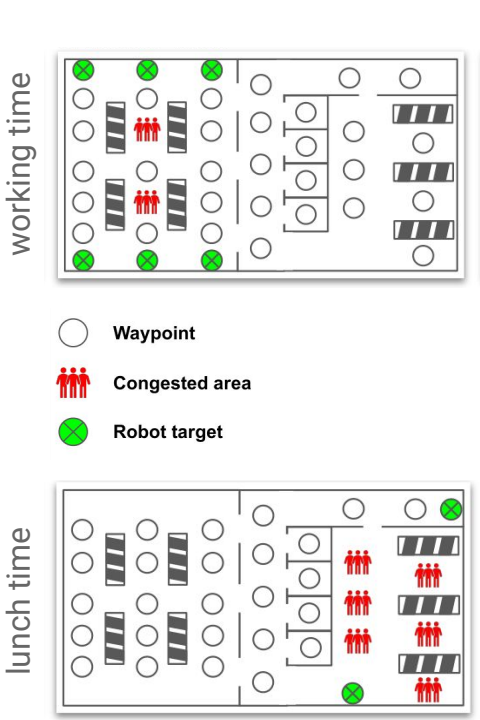




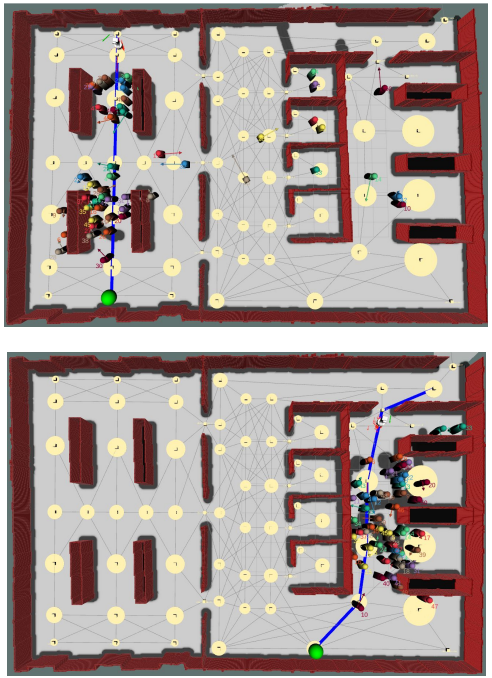
Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots use causal models to enhance decisions and interactions in human-shared spaces?



non-causal



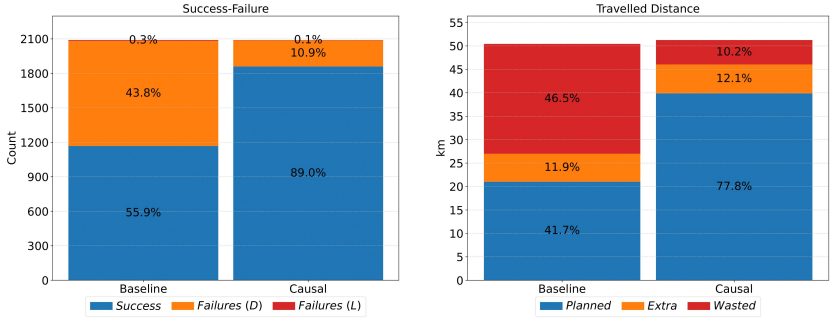
causal

Contributions

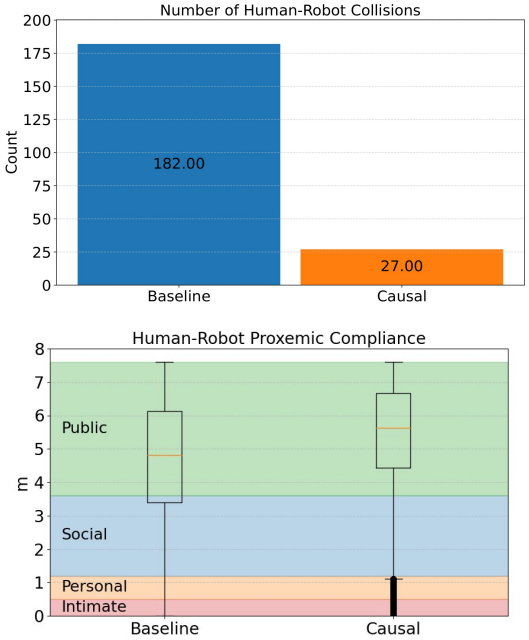
Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Can robots use causal models to enhance decisions and interactions in human-shared spaces?

efficiency



safety



Contributions

Integrating Causal Inference for Autonomous Robots in Dynamic Environments

Summing up

- Causality-enhanced decision-making framework for mobile robots in dynamic settings

Research outcomes

- Castri et al. “Causality-enhanced Decision-Making for Autonomous Mobile Robots in Dynamic Environments,” under review.

PeopleFlow

CausalFlow

A Unified Framework for Causality in Time-Series

A collection of causal discovery methods from time-series:

- CAnDOIT
- F-PCMCI
- PCMCI
- PCMCI+
- LPCMCI
- J-PCMCI+
- TCDF
- tsFCI
- DYNOTEARS
- VarLiNGAM

RandomGraph

- random systems of equations with(out) hidden confounders
- observational and interventional data from the generated graph
- various adjustable parameters (time-series length, obs vars, hidden vars, etc..)

Summary

Papers

- Castri et al. “Causal discovery of dynamic models for predicting human spatial interactions,” in International Conference on Social Robotics, 2022.
- Castri et al. “Enhancing causal discovery from robot sensor data in dynamic scenarios,” in Conference on Causal Learning and Reasoning, 2023.
- Castri et al. “CAnDOIT: Causal Discovery with Observational and Interventional Data from Time-Series”, Advanced Intelligent Systems, 2024.
- Castri et al. “Experimental Evaluation of ROS-Causal in Real-World Human-Robot Spatial Interaction Scenarios,” in IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), 2024.
- Castri et al. “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), 2024.
- Castri et al. “Causality-enhanced Decision-Making for Autonomous Mobile Robots in Dynamic Environments,” under review.

Software

CausalFlow

ROS-Causal

PeopleFlow

Personal webpage

Thank you!

Questions?