Sensor-driven Autonomous Path-following for Wheeled Mobile Robots

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Key Challenge

- Path-following for wheeled mobile robots (WMR) is a long-standing focus of research and development in robotics with many applications.
- Traditional provably correct methods assume knowledge of the robot location.
- **Sensor-driven navigation** with safety guarantees remains an open research question.

Fig. 1: General applications for path-following include self-driving cars and warehouse robots.

Approach: Sensor-based Score Function (SeBSF) Control

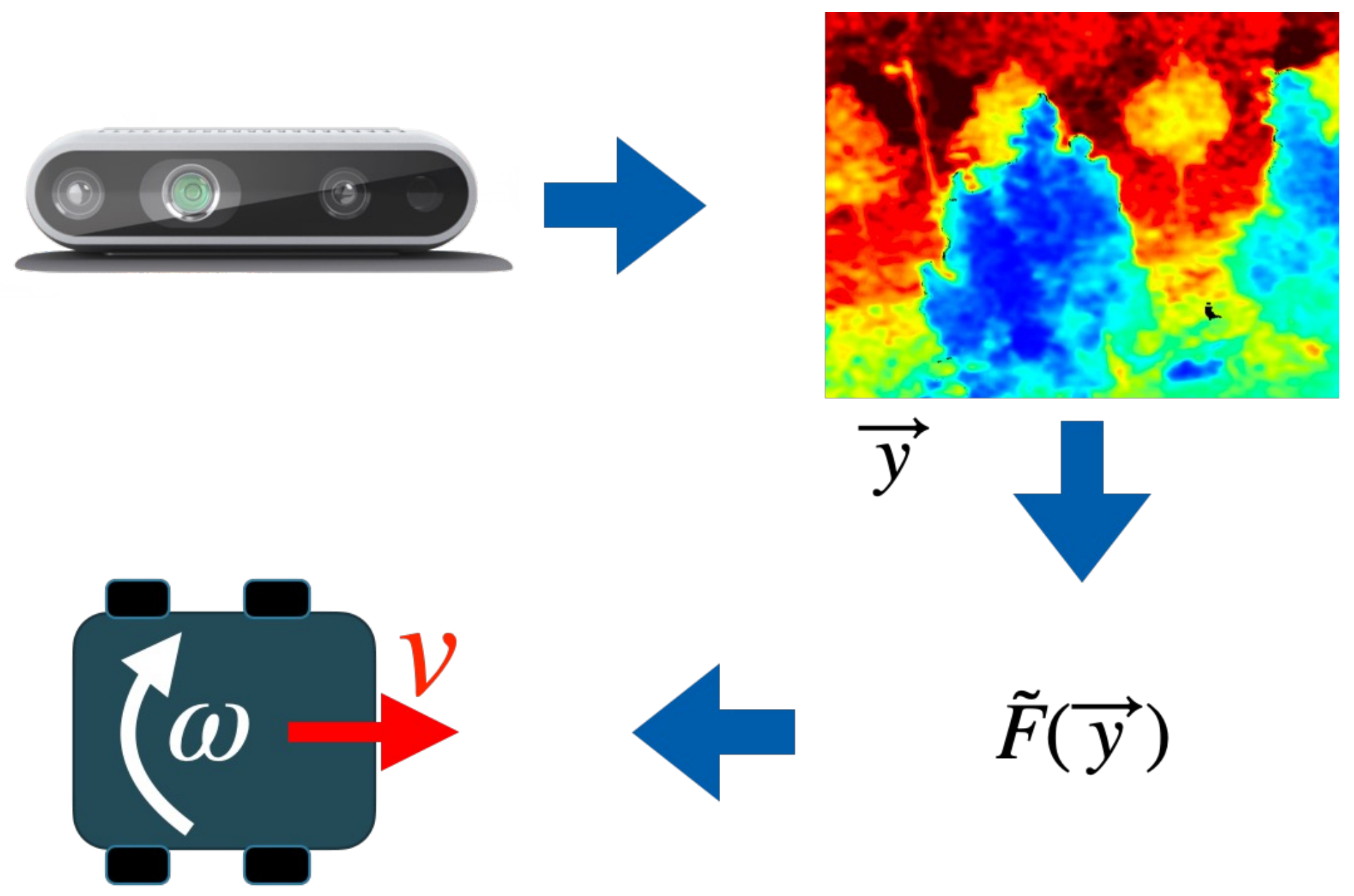

Fig. 2: SeBSF Control, without intermediate state estimation.

- We use a sensor-based score function (SeBSF) to distill high-dimensional sensor input $\vec{y}$ to a scalar value $\tilde{F}$.
- This scalar value is directly mapped to velocity inputs (v, ω) of the WMR

$$v = \beta e^{-\alpha \tilde{F}^2}$$

$$\omega = \gamma \tilde{F}$$

- $\alpha, \beta, \gamma > 0$ are design parameters

- To analyze this sensor-driven controller, we analyze the resulting kinematics in local path coordinates $\vec{x} = (\theta, d)$.
- θ is the heading w.r.t. path, and d is the distance from the path.
- In local coordinates $\vec{x}$, a measurement $H(\vec{x})$ is obtained, where H is the sensor model.
- A **key innovation** is that we do not need to know H to analyze the closed-loop.
- Consider the State-based Score Function (StBSF) $F(\vec{x}) = \tilde{F}(H(\vec{x}))$

Theorem 1: Let $\tilde{F}$ be a SeBSF, H be a sensor model, and $F = \tilde{F} \circ H$ be the resulting StBSF. If F satisfies the following conditions:

$$F(\vec{0}) = \vec{0}, \quad \frac{\partial F}{\partial \theta} < 0, \text{ and } \frac{\partial F}{\partial d} < 0,$$

and β/γ is sufficiently small, then the local path coordinates converge to a neighborhood of the origin whose size depends on the curvature of the path.

Results:

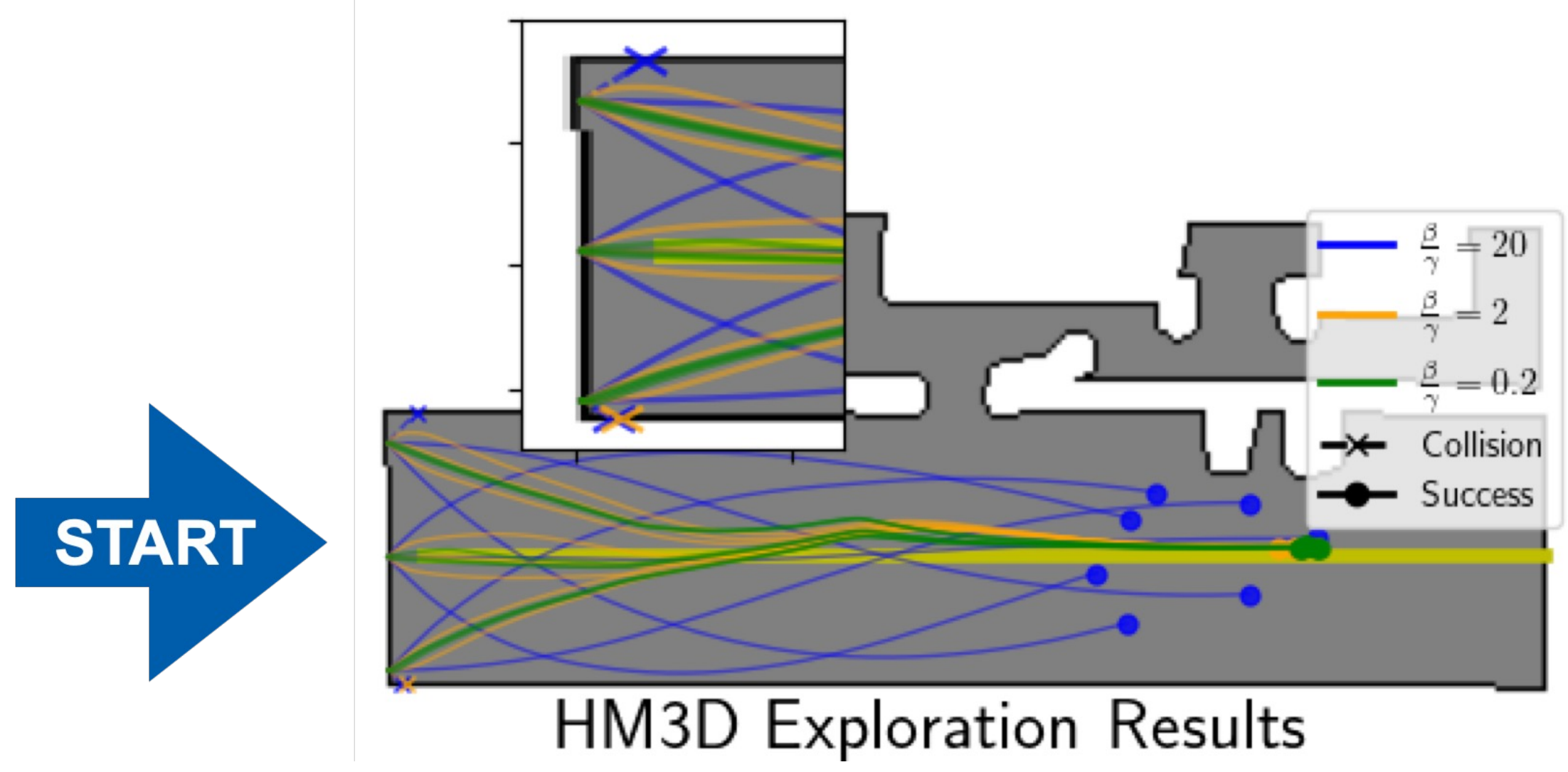

Fig. 3: Simulated path-following using AI Habitat simulator.

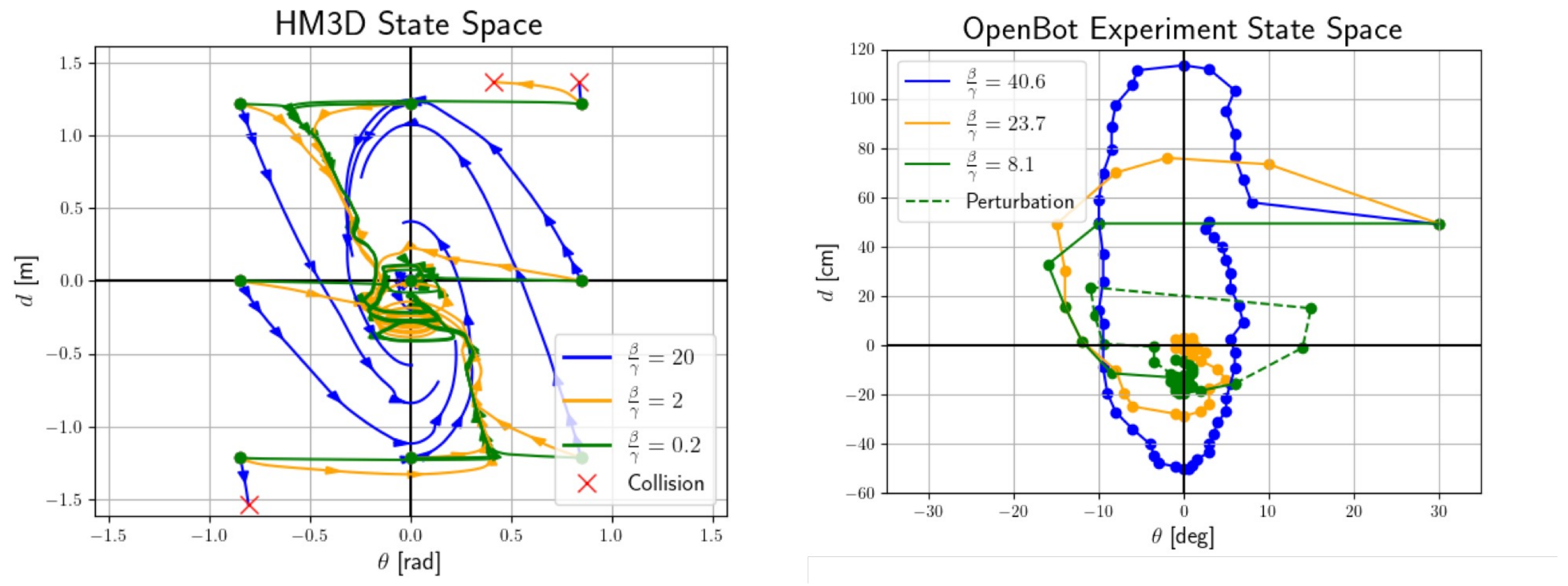

Fig. 4: Experiments on real robot replicate simulations despite lower sensor frequency.

Physical robot (OpenBot, Intel RealSense)

Preprint (arXiv)

Scientific Impact:

- Our analysis techniques may extend to second-order oscillators with damping and stiffness terms that depend on position and velocity, such as in biomechanical systems.
- The approach to path-following without explicit state feedback may be extended to systems with higher degrees of freedom, such as quadrotors or robot arms.
- Our approach provides a way to verify sensor-driven policies derived using machine learning techniques.

Contributions:

- We develop a novel analysis technique for 2D path-following kinematics where the dynamics in a state are highly uncertain due sensor-driven control using unknown measurement models.
- We demonstrate that controls-aware design enables a real robot to follow paths even when using simple machine learning models trained on very little data.

Broader Impacts:

- Organizations developing autonomous mobile robots can guarantee reliable navigation behaviour while using less computation and hardware resources devoted to navigation.

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