Confidence-aware motion prediction for real-time collision avoidance

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Work with Sylvia Herbert, Jaime Fisac, David Fridovich-Keil, Steven Wang, Sampada Deglurkar, Claire Tomlin and Anca Dragan
When robots observe behavior that is not well explained by their predictive models, how do they produce safe but efficient motions?
Confidence-aware prediction & planning

Connections to reachability analysis

Scaling up to multi-robot, multi-human scenarios
Confidence-aware prediction & planning

Connections to reachability analysis

Scaling up to multi-robot, multi-human scenarios
Noisily-Rational Human Motion Prediction

\[ P(\mathbf{u}_H | x_H; \theta, \beta) \propto e^{\beta Q(x_H, \mathbf{u}_H; \theta)} \]

\[ \dot{x}_H = f_H(x_H, \mathbf{u}_H) \]

[Schultz et al., ICRA 2017]
[Pfeiffer et al., IROS 2016]
[Finn et al., ICML 2016]
[Herman et al., ICRA 2015]
[Ziebart et al., AAAI 2008]
[Ramachandran et al., IJCAI 2007]

[Luce, 1959]
[Baker et al., 2007]
Robust Robot Planning with Human Predictions

\[ \dot{x}_R = f_R(x_R, u_R) \]
Robust Robot Planning with Human Predictions

\[
\dot{s}_R = \ddot{s}_R(s_R, a_R) \quad \text{vs.} \quad \dot{x}_R = f_R(x_R, u_R)
\]

[Lygeros, 2005]
[Mitchell, 2005]
[Herbert, 2017]
Robust Robot Planning with Human Predictions

Hamilton-Jacobi Reachability Analysis

\[ S_R = \int_R(s_R, a_R) \]

\[ \dot{r} = f_R(x_R, u_R) - \phi(f_R(s_R, a_R)) \]

\[ V(r, T) = \sup_{a} \inf_{u} \sup_{x_R} \left\{ \inf_{t=0}^{T} \sum_{t} \text{cost}(x_{t+1}^a(t)) \right\} \]

\[ r = f_R(x_R, u_R) - \phi(f_R(s_R, a_R)) \]

[Herbert, 2017]

[Lygeros, 2005]

[Mitchell, 2005]

Robust Robot Planning with Human Predictions

Hamilton-Jacobi Reachability Analysis

\[ \dot{x} = f_R(x_R, u_R) - \phi(f_R(s_R, a_R)) \]

\[ V(r, T) = \sup_{a[u]} \inf_{\tau \in [0,T]} \{ \sup_{\tau} \text{cost}(\xi^{u,a}_R(t)) \} \]

[Lygeros, 2005]

[Mitchell, 2005]

Robust Robot Planning with Human Predictions

Hamilton-Jacobi Reachability Analysis

\[ \dot{r} = f_R(x_R, u_R) - \phi(f_R(s_R, a_R)) \]

\[ V(r, T) = \sup_a \inf_t \{ \sup_u \{ \text{cost}(x_t, a(t)) \} \} \]

[Fisac, 2018]
[Lygeros, 2005]
[Mitchell, 2005]
[Herbert, 2017]
Robust Robot Planning with Human Predictions

$$P(\text{Crash}) > \text{collision}_{\text{thresh}}$$

[Fisac, 2018]
[Lygeros, 2005]
[Mitchell, 2005]
[Herbert, 2017]
Robust Robot Planning with Human Predictions

\[ P(\text{Crash}(\text{truck})) > \text{collision}_{\text{thresh}} \]
What if the predictive model is wrong?
Bayesian Model Confidence

\[ P(u_H \mid x_H; \theta, \beta) \propto e^{\beta Q(x_H, u_H; \theta)} \]

\[ \dot{x}_H = f_H(x_H, u_H) \]
Bayesian Model Confidence

\[
P(u_H \mid x_H; \theta, \beta) \propto e^{\beta Q(x_H, u_H; \theta)}
\]

\[
\dot{x}_H = f_H(x_H, u_H)
\]
Bayesian Model Confidence

\[ P(u_H \mid x_H; \theta, \beta) \propto e^{\beta Q(x_H, u_H; \theta)} \]

\[ \dot{x}_H = f_H(x_H, u_H) \]
Bayesian Model Confidence

\[ P(u_H \mid x_H; \theta, \bar{\beta}) \propto e^{\bar{\beta}Q(x_H, u_H; \theta)} \]

\[ \dot{x}_H = f_H(x_H, u_H) \]
Bayesian Model Confidence

\[ b^t(\beta) \propto P(u_H^t | x_H^t; \theta, \beta)b^{t-1}(\beta) \]

\[ \dot{x}_H = f_H(x_H, u_H) \]
Bayesian Model Confidence

\[ b^t(\beta) \propto P(u_H^t | x_H^t; \theta, \beta) b^{t-1}(\beta) \]
Fixed confidence \( \bar{\beta} \)

Bayesian confidence \( b^t(\beta) \)
Confidence-aware prediction

\[ h^*(\theta) \propto P(s_{t+1} \mid x_{t+1}, \theta, \beta) h^{t-1}(\beta) \]

Robust motion planning

\[ P(\text{Crash}(\bullet) > \text{collision}\_\text{thresh}) \]

Connections to reachability analysis

Scaling up to multi-robot, multi-human scenarios
Confidence-aware prediction

\[ b^t(\beta) \propto P(\omega^t | x^t_\beta; \theta, \beta) b^{t-1}(\beta) \]

Robust motion planning

\[ P(\text{Crash}(\cdot, \cdot)) > \text{collision}\_\text{thresh} \]

Connections to reachability analysis

Scaling up to multi-robot, multi-human scenarios
Forward Reachable Set

\[ FRS(x_H, t) := \{ x' : \exists u_H(\cdot), x' = \xi(x_H, t, u_H(\cdot)) \} \]
Forward Reachable Set

\[ h_x = v_H \cos(u_H) \]
\[ h_y = v_H \sin(u_H) \]

\[ \Delta t * v_H \]
Forward Reachable Set

\[ h_x = v_H \cos(u_H) \]
\[ h_y = v_H \sin(u_H) \]
Forward Reachable Set

\[
\begin{align*}
\dot{h}_x &= v_H \cos(u_H) \\
\dot{h}_y &= v_H \sin(u_H)
\end{align*}
\]
Forward Reachable Set

\[ h_x = v_H \cos(u_H) \]
\[ h_y = v_H \sin(u_H) \]
Forward Reachable Set

\[
\begin{align*}
\dot{h}_x &= v_H \cos(u_H) \\
\dot{h}_y &= v_H \sin(u_H)
\end{align*}
\]
Forward Reachable Set

\[
\begin{align*}
\dot{h}_x &= v_H \cos(u_H) \\
\dot{h}_y &= v_H \sin(u_H)
\end{align*}
\]

\[P_{coll} \to 0\]
Forward Reachable Set

\[
\begin{align*}
\dot{h}_x &= v_H \cos(u_H) \\
\dot{h}_y &= v_H \sin(u_H)
\end{align*}
\]
Forward Reachable Set

\[ h_x = v_H \cos(u_H) \]
\[ h_y = v_H \sin(u_H) \]

\[ 1 \text{ sec} \times v_H \]

\[ 2 \text{ sec} \times v_H \]

\[ 3 \text{ sec} \times v_H \]

\[ \beta \text{-Bayes State Distribution} \]
Connections between predictions and FRS

Confidently determining subsets of the FRS to avoid

Scaling up to multi-robot, multi-human scenarios
Scaling up to multi-robot, multi-human scenarios

Connections between predictions and FRS

Determining subsets of the FRS to avoid

Confidence-aware prediction

Robust motion planning
1000 x 1000 x 1000 = 1B

1000 x 1000 x 1000 x 1000 = 1T

1000 x 1000 = 1M

1000 x 1000 x 1000 = 1B

1000 x 1000 x 1000 x 1000 = 1T
Hardware Demonstration
Confidence-aware prediction offers promising directions for scaling.

Connections between predictions and FRS

Determining subsets of the FRS to avoid

Confidence-aware predictions offer promising directions for scaling.
Confidence-aware prediction

\[ b^t(\beta) \propto P\left( m^t | x^t; \theta, \beta \right) b^{t-1}(\beta) \]

Robust motion planning

\[ P(\text{Crash}(\bullet)) > \text{collision\_thresh} \]

Connections between predictions and FRS

Determining subsets of the FRS to avoid

Confidence-aware predictions offer promising directions for scaling
Papers


Code

Multi-robot, multi-human planning: https://github.com/HJReachability/faSTPeople
Fast and safe robot tracking: https://github.com/HJReachability/fastrack
Pedestrian prediction: https://github.com/shwang/pedestrian_prediction
ROS wrapper for pedestrian prediction: https://github.com/abajcsy/crazyflie_human