Anticipatory Robot Navigation: Incorporating Estimated Obstacle Behaviors with the Social Force Model

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Background

- Increasing demand for automation within warehouses.
- Robots are central to warehouse automation.
  - e.g. Automated Guided Vehicles (AGVs).
  - Primarily perform transport tasks.
- Some obstacles exist in the operational area of the robot.
  - Static Obstacles: Walls, etc.
  - Dynamic Obstacles: Humans, other robots, etc.
- Challenge: Obstacle Avoidance
  - At the situations with unclear obstacle behavior, we focus on:
    - Navigate the robot to achieve an optimal balance between navigation safety and moving efficiency.

Traditional Collision Avoidance Methods

- Drawback: Lack of Interaction-Awareness in some traditional methods.
  - Neglecting the impact of robot's movement on obstacle trajectories.
  - Leads to perceiving higher obstacle intrusion and conservative control strategies, e.g., stopping or speed reduction[1].
  - In extreme situations, leads to Freezing Robot Problem[2].

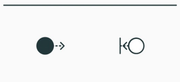

Figure 1: Example: Robot stopped due to lack of Interaction-Awareness.

[1]Milos Vasic and Aude Billard. Safety issues in human-robot interactions. In 2013 IEEE International Conference on Robotics and Automation (ICRA), pages 197-204, 2013.
[2]Peter Trautman and Andreas Krause. Unfreezing the robot: Navigation in dense, interacting crowds. In 2010 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pages 797-803, 2010

Development of Interaction-Aware Methods

- Introduction of the Social Force Model.
  - To understand and predict the interaction between surrounding entities.
- Drawback: Ignoring individual obstacles behavior.
  - Tendency to use fixed parameter values across different scenarios.
  - Challenges in accurately predicting diverse obstacle behaviors.
  - Potential risk of misjudging obstacle actions leading to collision or inefficient navigation.

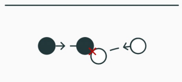

Figure 2: Example: Collision risk due to misjudgment in obstacle behavior.

Proposal

Navigating robots while ensuring smooth and efficient movement.

- Model and predict the individual obstacles behavior using observational position data.
  - Utilizing the Social Force Model to simulate obstacle behavior.
  - Adapting model parameters based on observed behaviors of different obstacles.
- Calcuate control input of the robot.
  - Based on the model of the behaviors of nearby obstacles.

Assumption

- The robots' observation of the obstacles' position $\tilde{\boldsymbol{r}}_o(t)$ contains noises, potentially due to sensor precision.

Social Force Model

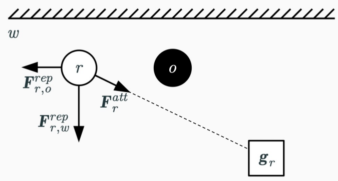

Figure 3: An example for Social Force Model.

For the robot r : $\boldsymbol{F}^{rep}_{r,o}(t) = A_r \cdot e^{-||\boldsymbol{d}_{r,o}(t)||/B} \frac{\boldsymbol{d}_{r,o}(t)}{||\boldsymbol{d}_{r,o}(t)||}, \ \boldsymbol{F}^{att}_{r}(t) = \frac{1}{\tau}(\mathbf{v}^0_r(t) - \mathbf{v}_r(t)).$

For the obstacle o : $\boldsymbol{F}^{rep}_{o,r}(t) = A_o \cdot e^{-||\boldsymbol{d}_{o,r}(t)||/B} \frac{\boldsymbol{d}_{o,r}(t)}{||\boldsymbol{d}_{o,r}(t)||}, \ \boldsymbol{F}^{att}_{o}(t) = \frac{1}{\tau}(\mathbf{v}^0_o(t) - \mathbf{v}_o(t)).$

Method Overview

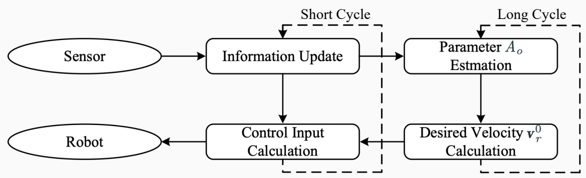

Figure 4: The procedure of control.

Method: Short Cycle

Employ the Kalman filter to refine the observed position of an obstacle, by

$$\widehat{\mathbf{r}}_o(t) = \widehat{\mathbf{r}}'_o(t) + \left[\boldsymbol{K}(t) \cdot \left(\widetilde{\mathbf{r}}_o(t) - \widehat{\mathbf{r}}'_o(t)\right)\right].$$

Here, the estimation of velocity is given by

$$\widehat{\mathbf{v}}_o(t) = \frac{\widehat{\mathbf{r}}_o(t) - \widehat{\mathbf{r}}_o(t - \Delta t) + 1/2 \cdot \widehat{\mathbf{a}}_o(\Delta t) \cdot \Delta^2 t}{\Delta t}.$$

Then, the control input of the robot is calculated by

$$\mathbf{v}_r(t + \Delta t) = \mathbf{v}_r(t) + \mathbf{a}_r(t)\Delta t.$$

Here, $\mathbf{a}_r(t)$, the acceleration, is determined by the Social Force Model. The parameter for the Social Force Model are defined according to the long circle.

Method: Long Cycle

Estimate the value of the parameter A_o using Bayesian Estimation by

$$P(A_o^i | \widetilde{\mathbf{r}}_o(t), \widetilde{\mathbf{r}}_o(t - \Delta t)) = \frac{L\left(\widetilde{\mathbf{r}}_o(t) | A_o^i, \widetilde{\mathbf{r}}_o(t - \Delta t)\right) \cdot P(A_o^i)}{\sum_i L\left(\widetilde{\mathbf{r}}_o(t) | A_o^i, \widetilde{\mathbf{r}}_o(t - \Delta t)\right) \cdot P(A_o^i)}.$$

This parameter is crucial for dictating the avoidance behavior of obstacles and predicting their movement.

Then, calculate the desired velocity by minimize the objective function

$$minimize \quad \mathcal{J}([\mathbf{v}_r^0]) = \mathcal{J}_t([\mathbf{v}_r^0]) + \mathcal{P}_v([\mathbf{v}_r^0]) + \mathcal{P}_d([\mathbf{v}_r^0])$$

based on the prediction of trajectories. This parameter is crucial for calculate the control input of the robot, achieve an optimal balance between navigation safety and operational efficiency.

Evaluation: Experimental Setup

- **Environment:** Flat area of $3m \times 3m$.
- **Robot and Obstacle Settings:** Detailed in Table 1.
- **Simulation Cases:**
  - Obstacle avoids the robot ($A_o = 20$).
  - Obstacle maintains original trajectory ($A_o = 0$).

Table 1: Settings for the Robot and the Obstacle

	Obstacle o	Robot r
Initial position $\boldsymbol{r}(0)$	$[1.5, 0.8]$	$[1.5, 2.2]$
Initial velocity $\boldsymbol{v}(0)$	$[0, 1]$	$[0, -1]$
Goal g	$[1.5, 2.2]$	$[1.5, 0.8]$
Maximum speed v_{max}	$1.5m/s$	$1.5m/s$

Figure 5: Setting

Evaluation: Estimation of the Obstacles Behavior

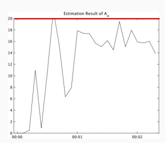

Figure 6: Estimation result $\widehat{A}_o$ when the actual value of A_o is set to 20.

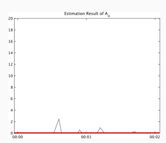

Figure 7: Estimation result $\widehat{A}_o$ when the actual value of A_o is set to 0.

Evaluation: Comparison With the Scenario Without Parameter Estimation

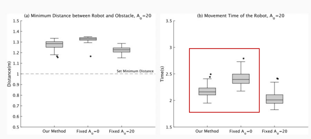

Figure 8: The results where $A_o = 20$, indicate that the obstacle will attempt to avoid the robot.

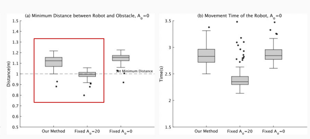

Figure 9: The results where $A_o = 0$, indicate that the obstacle will not attempt to avoid the robot.

Conclusion

Summary of Current Work

- Applied the Social Force Model for understanding and predicting obstacle avoidance behaviors.
- Utilized these insights to refine the robot's control input.
- Achieved a balance between navigation efficiency and safety.

Future Directions

- Exploration of practical application in real-world scenarios.
- Deployment and testing on actual robots in diverse environments.
- Expansion of the model to include human obstacles and account for irrational behaviors.