Combining Social Force Model with Model Predictive Control for Vehicle's Longitudinal Speed Regulation in Pedestrian-Dense Scenarios

Dongfang Yang, Teawon Han, and Ümit Özgüner
Department of Electrical and Computer Engineering, The Ohio State University, Columbus, Ohio, 43210

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Introduction

In pedestrian-dense traffic scenarios, an autonomous vehicle may have to safely drive through a crowd of pedestrians while the vehicle tries to keep the desired speed as much as possible. This requires a model that can predict the motion of crowd pedestrians and a method for the vehicle to predictively adjust its speed. In this study, the model-based predictive control (MPC) was combined with a social-force based vehicle-crowd interaction (VCI) model to regulate the longitudinal speed of the autonomous vehicle. The predictive feature of the VCI model can be precisely utilized by the MPC. A criterion for simultaneously guaranteeing pedestrian safety and keeping the desired speed was designed, and consequently, the MPC was formulated as a standard quadratic programming (QP) problem, which can be easily solved by standard QP toolbox. The proposed approach was compared with the traditional proportional-integral-derivative (PID) control approach for regulating longitudinal speed. Scenarios of different pedestrian density were evaluated in simulation. The results demonstrated the merits of the proposed method to address this type of problem. It also shows the potential of extending the method to address more complex vehicle-pedestrian interaction situations.

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CONTACT

Contact: yang.3455@osu.edu
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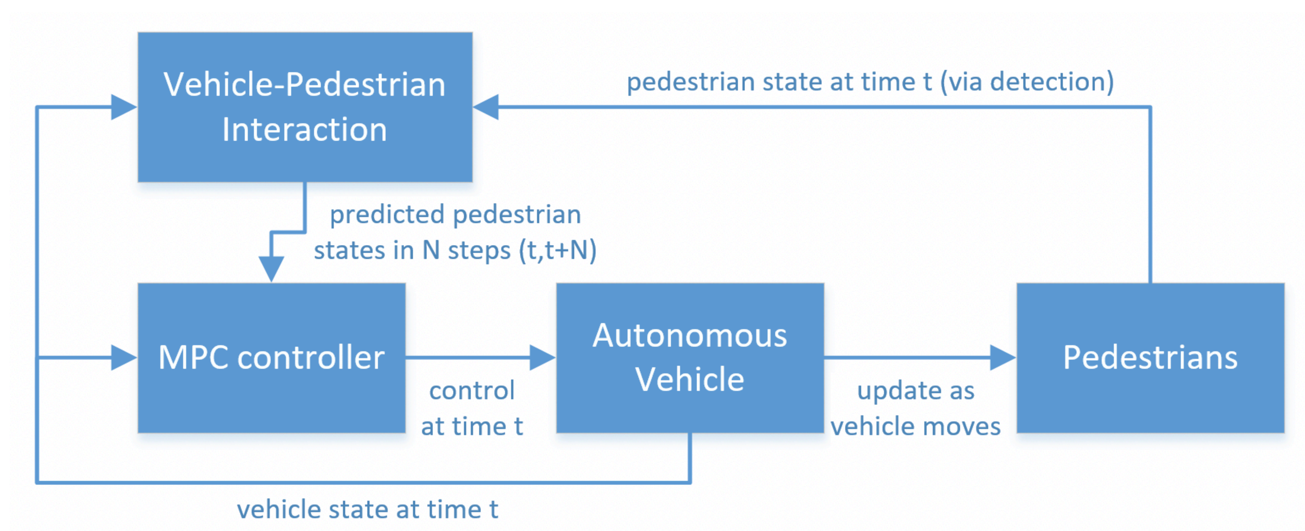
Framework



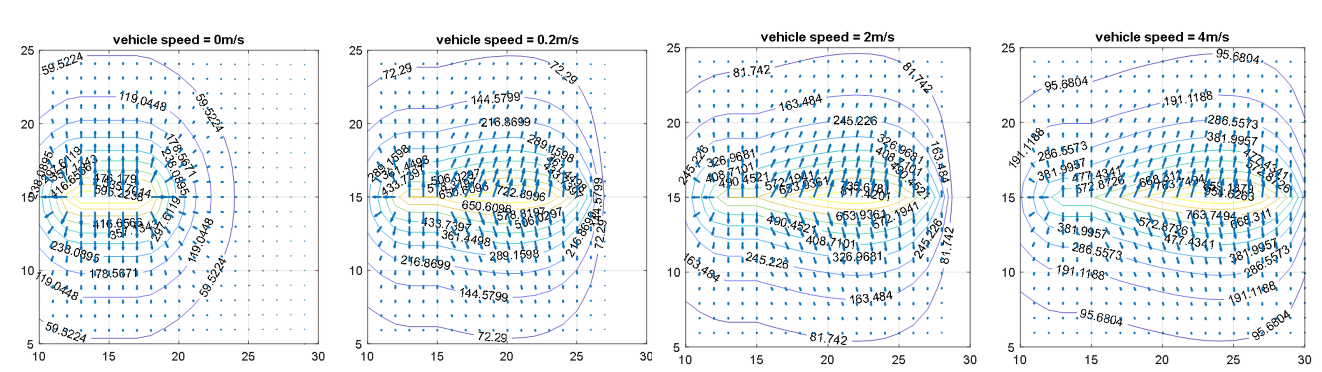
Pedestrian Motion Modeling

The motion dynamics of each pedestrian is described by a social force based vehicle-crowd interaction (VCI) model:

$$\frac{d^2x_i}{dt^2} = \frac{v_i}{dt} = a_i = \frac{F_i}{m},$$

$$F_i = \sum_{j\in Q(i)} (f_r^{ij} + f_c^{ij} + f_n^{ij}) + f_v^i + \beta_i(f_v^i)\cdot f_d^i.$$

social forces from nearby pedestrians:	vehicle influence:	destination force:
f_r^{ij}: repulsion f_c^{ij}: collision f_n^{ij}: navigation	f_v^i: force from vehicle $\beta_i(f_v^i)$: adjusting destination force	f_d^i: driving pedestrian to the target



Examples of vehicle influence at different longitudinal speed.

Crowd Motion Prediction:

- Assumption 1: all pedestrian state at $t = t'$ can be correctly obtained
- Assumption 2: vehicle will move linearly and constantly based on current velocity
- Pedestrian motion at $t > t'$ is predicted by iteratively applying the VCI model

Vehicle Dynamics

Longitudinal Dynamics: $M\ddot{s}(t) + \alpha\dot{s}(t) = F_t(t) - F_b(t)$

Let $x = [x_1, x_2]^T = [s, \dot{s}]^T$ be the longitudinal position and speed, with discretization time Δt, we have:

$$x(k+1) = Ax(k) + Bu(k)$$

$$A = \begin{bmatrix} 1 & \Delta t \\ 0 & 1-\frac{\alpha\Delta t}{M} \end{bmatrix}, B = \begin{bmatrix} 0 \\ \frac{\Delta t}{M} \end{bmatrix}, u(k) = F_t(k) - F_b(k).$$

MPC Synthesis

At time step k, future vehicle state:

$$x(k+n|k) = A^n x(k) + A^{n-1}Bu(k|k) + A^{n-2}Bu(k+1|k) + \cdots + ABu(k+n-2|k) + Bu(k+n-1|k). \quad (4)$$

Then, formulate a N horizon MPC problem:

$$X = S_x x_k + S_u U \qquad X = \begin{bmatrix} x(k+1) \\ x(k+2) \\ \vdots \\ x(k+N) \end{bmatrix} \in \mathbb{R}^{2N}, \quad S_x = \begin{bmatrix} A \\ A^2 \\ \vdots \\ A^N \end{bmatrix} \in \mathbb{R}^{2N\times 2},$$

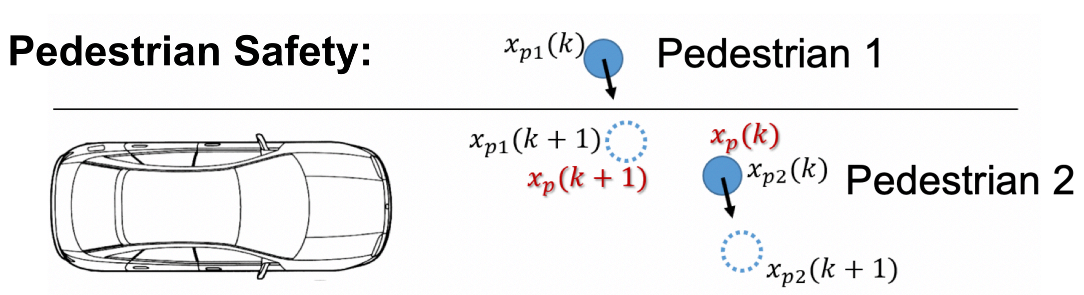
$$S_u = \begin{bmatrix} B & 0 & \dots & 0 \\ AB & B & \dots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ A^{N-1}B & \dots & AB & B \end{bmatrix} \in \mathbb{R}^{2N\times N}, \quad U = \begin{bmatrix} u(k) \\ u(k+1) \\ \vdots \\ u(k+N-1) \end{bmatrix} \in \mathbb{R}^N, x_k = x(k) \in \mathbb{R}^2.$$

Constraints:

Control Action: $|u(i)| \le u_{max}$, $|\Delta u(i)| \le \Delta u_{max}$. $\forall i = k+1, \dots, k+N$

Speed: $v_{min} \le x_2(i) \le v_{max}, \forall i = k+1, \dots, k+N.$

Pedestrian Safety:



$$x_1(i) - x_p(i) \ge d_{safe}, \forall i = k+1, \dots, k+N$$

Objective: find control $U = [u(k), u(k+1), \cdots, u(k+N-1)]^T$ at every $x(k)$ to satisfy safety constraints and to keep desired speed v_d as much as possible.

$$J(k) = (A_r X - V_r)^T Q (A_r X - V_r)$$

A_r: extracts velocity from X; V_r: speed reference vector.

Convert to **QP problem**:

$$U^* = \arg\min_U (U^T H U + 2FU + Y)$$

$$H = S_u^T A_r^T Q A_r S_u$$

$$F = (A_r S_x x_k - V_r)^T Q A_r S_u$$

$$Y = (A_r S_x x_k - V_r)^T Q (A_r S_x x_k - V_r) = const.$$

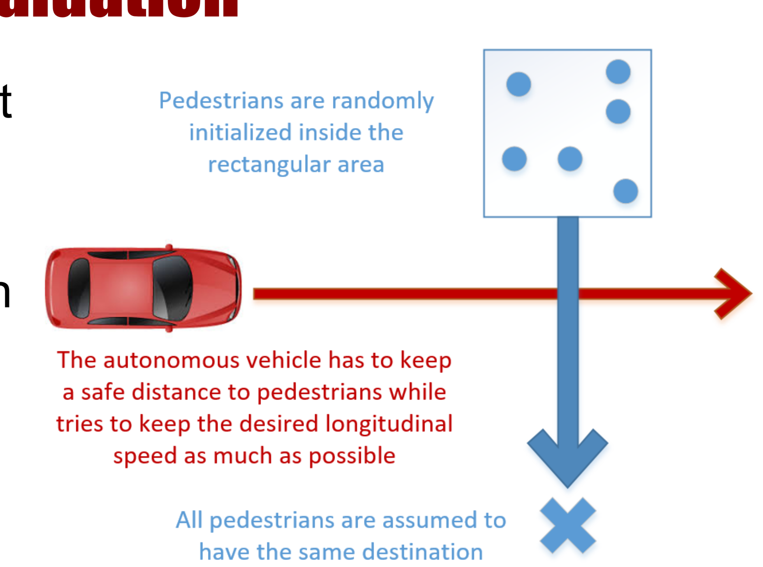
Evaluation

Criterion: total time spent to complete the vehicle-pedestrian interaction

Compare: MPC approach vs. PID approach

Simulation was done in Matlab Simulink

- Repeated 2000 times,
- For each simulation:
  - 30 pedestrians are randomly initiated
  - For both approaches, pedestrian pattern is the same



Results

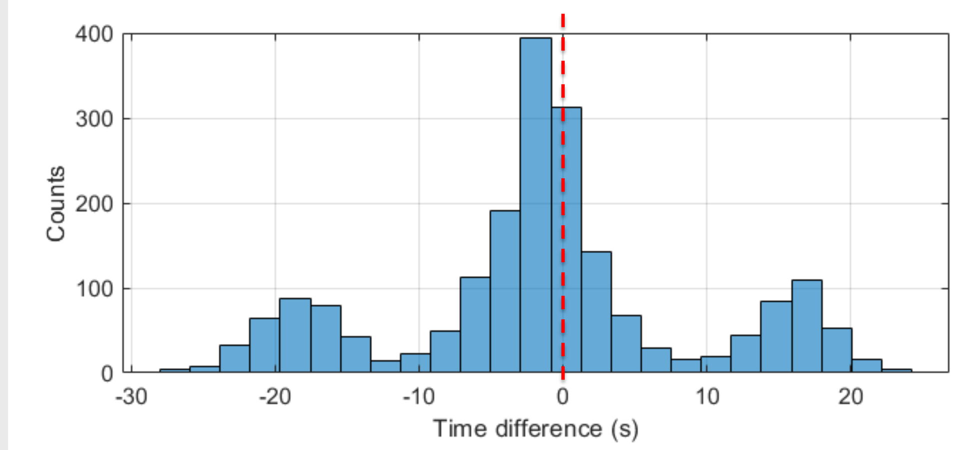
Different vehicle motion patterns appear in simulation:

- Stop and yield;
- Slightly slow down;
- Drive through without slowing down (the vehicle predicts that pedestrians will yield)

Results have been categorized in 3 different situations:

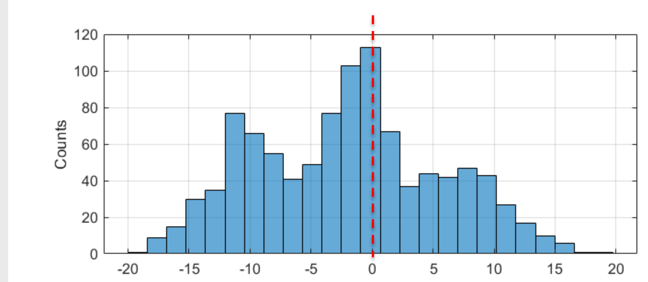
- **General Situation:** all simulation results
- **Stop-and-Wait Situation:** both MPC and PID approaches stop and wait for pedestrian crossing
- **Non-stop Situation:** both MPC and PID approaches do NOT stop and wait

Evaluate the **difference** of the total time spent to complete the interaction between MPC and PID: $t_{MPC} - t_{PID}$

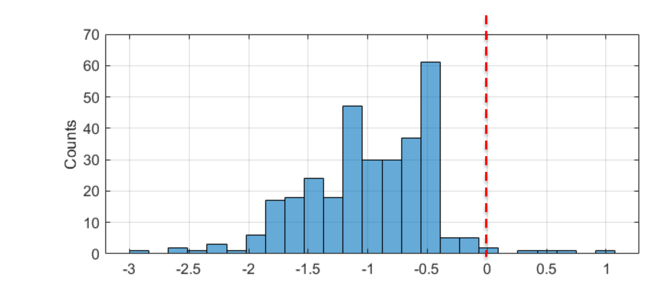


General Situation

Scan me
Simulation Video



Stop-and-Wait Situation



Non-stop Situation

For different pedestrian density:

Average time difference between MPC and PID approaches

# of Ped.	General	Stop-and-Wait	Non-stop
30	-1.2665	-1.9457	-0.9843
20	-0.5243	-1.8338	-0.7630
10	-0.4153	N.A.	-0.5394

CONCLUSIONS

This study combined social force based pedestrian motion model with the model predictive control (MPC) approach for longitudinal vehicle speed regulation. A scenario of interacting crossing pedestrians is formulated and then converted into a standard quadratic programming (QP) problem, which is solved by standard toolbox. The merits of the proposed approach was confirmed in the simulation results.

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