Cooperative Motion Control of Multiple Autonomous Marine

Collision Avoidance in Dynamic Environments

EECI Graduate School on Control

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Outline

• Motivation/Objectives
• Cooperative Motion Control Architecture
• Collision Avoidance System
  – Predicting a Collision
  – Collision Avoidance
• Simulation
• Results/Study case scenarios
Motivation/Objectives

- Vehicles performing a cooperative mission may encounter unforeseen obstacles
Motivation/Objectives

- Vehicles performing a cooperative mission encounter unforeseen obstacles

Objectives

- Development of a collision avoidance system in dynamic environments
  - Collision prediction module (Multimodel Kalman filter)
  - Collision avoidance (path re-planning using Harmonic potential fields or controlling the velocity)
- Integration into the cooperative motion control architecture
- Development of a Matlab simulator platform
Cooperative Motion Control

Architecture

Mission/Path Plan

Agents 1 2 ... n

Environment

Vi

obstacle
currents
dark area
Cooperative Motion Control

**Agents**

- **Path-Following Controller**
  - Input: predefined path and velocity profile
  - Output: commands that drive the vehicle to the desired path

- **Coordination Controller**
  - Input: the position of the variables that parameterizes the path of each vehicle that communicates with it
  - Output: The velocity command to correct the vehicle’s position in the formation

**Architecture**

Collision Avoidance is implemented at the coordination level, together with the Path-Following controller.
Cooperative Path-following
Collision Avoidance System

Operates on the vehicle's desired Paths and Velocities

Hierarchy Model

1. Target Tracking & Collision Prediction
2. Collision avoidance
   - Path re-planing
   - Velocity Control

Collison Avoidance System

Vigilant State

Cooperative Motion Control

Collision Prediction Module

Target tracking

Prediction

Collision Avoidance

Path Following Controller Vehicle

1. Obstacle detected in the vicinity of the vehicle
2. Obstacle approaching the vehicle
3. Imminent collision detected
4. Collision free path
5. Collision avoidance maneuver completed
6. Obstacle out of tracking range
Collision Prediction Module

• Tracks the Target by computing estimates for $v$ and $w$

- Obstacle (target) dynamic model

\[
\begin{align*}
\dot{x} &= v \cos \theta \\
\dot{y} &= v \sin \theta \\
\dot{\theta} &= \omega
\end{align*}
\]

• Compares the Targets probable trajectory with the vehicle path
Collision Prediction Module

Interactive Multi Model Kalman Filter

- Bank of KF running in parallel
- Output is the weighted sum of the state estimations produced by each KF

State Model

\[
\begin{align*}
    x^j_{k+1} &= x^j_k + t_s v^j_k \cos \theta^j_k \\
    y^j_{k+1} &= y^j_k + t_s v^j_k \sin \theta^j_k \\
    \theta^j_{k+1} &= \theta^j_k + t_s \omega^j_k + \eta^j_{\theta k} \\
    v^j_{k+1} &= v^j_k + \eta^j_{v k}
\end{align*}
\]

\[
\omega^j \in [w_{min}, w_{max}]
\]
Collision Prediction Module

Interaction/Mixing

Bank of EKF

Mode Probability Update

State Estimate And Covariance Combination

Measurement

$y_{k+1}$

$P^{o_j}(k | k)$

$\hat{x}^j(k | k)$

$P^{o_j}(k | k)$

$P^{j}(k | k)$

$\hat{x}(k+1 | k+1)$

$\mu_j(k)$

$\bar{z}$

$1/z$

$P(k+1 | k+1)$

$EKF 1$

$EKF 2$

$EKF n$

$1/z$
Collision Prediction Module

\[
W^{t_0} = [t_0, t_0 + \delta]
\]

\[
\delta = \frac{v_0}{a} + \zeta
\]

- \( v_0 \) – velocity of the vehicle at time instant \( t_0 \)
- \( a \) – maximal breakage deceleration of the vehicle undergoing translational motion
- \( \zeta \) – desired safety margin
Collision Prediction Module

\[ W^{t_0} = [t_0, t_0 + \delta] \]
\[ \delta = \frac{v_0}{a} + \zeta \]

\( A^{0}_{vh} \) - polygonal region that bound the area occupied by the vehicle at \( t_0 \)

\( A^{0}_{ob} \) - idem, but for the obstacle

\[ A^t_{vh} = \Phi_v(x_v(\cdot), y_v(\cdot), A^0_{vh}), \quad \forall t \in W^{t_0} \]
\[ A^t_{ob} = \Phi_o(x_o(\cdot), y_o(\cdot), A^0_{ob}), \quad \forall t \in W^{t_0} \]
Collision Prediction Module

\[ W^{t_0} = \left[ t_0, t_0 + \delta \right] \]
\[ \delta = \frac{v_0}{a} + \zeta \]

\( A_{vh}^0 \) – polygonal region that bound the area occupied by the vehicle at \( t_0 \)

\( A_{ob}^0 \) – idem, but for the obstacle

\[ A_{vh}^{t_c} \cap A_{ob}^{t_c} \neq \emptyset \]
Collision Avoidance – Path Planning

Spatially deconflict the paths

Artificial potential approach

- The obstacles to be avoided are represented by a repulsive artificial potential, and the goal is represented by an attractive potential
- Fast Computation

- Harmonic Potential Fields
  - Free from local minima

• Goal

\[ \phi_g = \frac{\lambda_g}{2\pi} \ln\left(\sqrt{(x - x_g)^2 + (y - y_g)^2}\right) \]

• Uniform Field

\[ \phi_u = -U(x \cos \alpha + y \sin \alpha) \]

• Panel method

\[ \phi(x, y) = \frac{\lambda}{4\pi} \int_{-L}^{L} \ln \sqrt{x^2 + (y - l)^2} \, dl \]
\[ \phi_{total} = \phi_g + \phi_u + \phi_{ob} \]

- **Condition**

\[ -\lambda_g > \lambda_{ob} > 0 \]

Collision Avoidance – Path Planning

- A free path to the goal is obtained following the velocity field $v$

$$v = -\nabla \phi_{total}$$

$$v_x(x, y) = U \cos \alpha - \frac{\lambda_g}{2\pi} \frac{\partial}{\partial x} \ln R_g - \sum_{j=1}^{m} \int_j \frac{\partial}{\partial x} \ln R_j dl_j$$

$$v_y(x, y) = U \sin \alpha - \frac{\lambda_g}{2\pi} \frac{\partial}{\partial y} \ln R_g - \sum_{j=1}^{m} \int_j \frac{\partial}{\partial y} \ln R_j dl_j$$
Potential Field Path Planning

Diagram showing path planning for multiple vehicles, each with different speeds (V1, V2, V3) in a 2D space.
Potential Field Path Planning
Potential Field Path Planning
Velocity Correction

Idea: Change the speed that the vehicle travels along the path to avoid collision with a dynamic obstacle
Velocity Correction

The virtual target avoids collision for:

\[(\gamma_g, t_g) \rightarrow (\gamma_A, t_f)\]
\[(\gamma_g, t_g) \rightarrow (\gamma_B, t_i)\]

\[(\gamma_g, t_g) \rightarrow (\gamma_A, t_f)\] → Deceleration

- Inter-vehicle coordination is achieved through Right of way
  - Priority is granted to the vehicle traveling on starboard tack
  - Correction action is taken by the vehicle traveling on the left
Scenario 1 – Dynamic Obstacle
Scenario 2 – Dynamic Obstacle
Scenario 3 – Bottleneck
Conclusions

- We proposed a collision avoidance system for autonomous vehicles working in dynamic environments, and showed how to integrate it in a typical cooperative motion control architecture.

- The problem was decoupled into:
  - a collision prediction stage (multi-model Kalman filter), and
  - a collision avoidance maneuver (path re-planning using Harmonic potential fields or controlling the velocity).

- The efficiency of the solutions was illustrated in simulation.