THE AUTOSEA PROJECT:
Developing closed-loop target tracking and collision avoidance systems

AUTOSEA – facts and figures

- Funded under the MAROFF program of the Research Council of Norway.
- Budget 11MNOK, with contributions from DNV GL, Kongsberg Maritime and Maritime Robotics.
- Duration: August 2015-August 2019.
- The project funded 2 PhD candidates and one postdoctoral fellow.
- In addition, 2 PhD candidates and around 30 MSc candidates are/have been affiliated with the project.

Developed and demonstrated methods for sensor fusion and collision avoidance for autonomous surface vehicles.
Collision avoidance for autonomous ships

AIS

Link to operator

Collision avoidance module

Collision detection

Collision avoidance

Guidance

Charts

Target tracking

Navigation

Collision detection

Collision avoidance

Control system

Actuators

Sensor fusion module

Target tracking

Navigation

Imaging sensors

Navigation sensors

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Sensor fusion module

Collision avoidance for autonomous ships

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Navigation sensors

Charts

Sensor fusion module
Different types of uncertainties

- Kinematic estimation uncertainty
- Data association uncertainty
- Ownship guidance uncertainty
- Target vessel intention uncertainty
Model predictive control (MPC)

Try several control inputs and choose the one that gives most desirable behavior.

Key design choices include parametrization (of both control input and cost function) and search technique.
## COLAV methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Objective function</th>
<th>Constraints</th>
<th>Search strategy</th>
<th>Input parametrization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity Obstacle (VO)</td>
<td>Deviation of velocity + time to collision</td>
<td>Kine. + Risk + CC</td>
<td>Grid search</td>
<td>Des. Course + Speed</td>
</tr>
<tr>
<td>Dynamic Window (DW)</td>
<td>Deviation of velocity + Risk</td>
<td>Kine. + Risk</td>
<td>Grid search</td>
<td>Des. Yaw-rate + Speed</td>
</tr>
<tr>
<td>Mid-level</td>
<td>Deviation of trajectory + RAM</td>
<td>Kine. + Risk + CC</td>
<td>Gradient search</td>
<td>Course + speed (time-parameterized)</td>
</tr>
<tr>
<td>Branching-course MPC (BC-MPC)</td>
<td>Deviation of trajectory + Risk + CC + Trans.</td>
<td>Kine.</td>
<td>Grid search</td>
<td>Segmented trajectory</td>
</tr>
</tbody>
</table>

CC = COLREGS compliance  
RAM = Readily Apparent Maneuvers  
Kine. = Kinematics limitations  
Trans. = Transition costs
## COLAV methods

<table>
<thead>
<tr>
<th></th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO</td>
<td>Simple and intuitive. COLREGS easily included.</td>
<td>Assumes instantaneous change to desired velocity.</td>
</tr>
<tr>
<td>DW</td>
<td>Direct control of yaw-rate gives powerful maneuvers.</td>
<td>Maneuvers not readily apparent.</td>
</tr>
<tr>
<td>SB-MPC</td>
<td>Flexible and economic cost function. Thoroughly verified in experiments.</td>
<td>Does not accommodate sequences of plans (in current version).</td>
</tr>
<tr>
<td>Mid-level</td>
<td>Can plan far ahead in time (essentially a global method)</td>
<td>Susceptible to local minima.</td>
</tr>
<tr>
<td>BC-MPC</td>
<td>Gives readily apparent maneuvers.</td>
<td>Less elegant cost function than SBMPC.</td>
</tr>
</tbody>
</table>
Why MPC: Explainability

Can the system explain its own reasoning?

Cost function

- Radar tracks / AIS
- Charts
- COLREGS
- Maneuverability
- Environment
- Overriding control input
- Safe trajectory
- Scenario
Explainability in sensor fusion ⇒ Bayesian inference

All sensor information is qualified by tracking algorithms with Bayesian underpinnings before entering the control system.

Bayes’ rule

- Sensor data (radar etc.)
- Physical intuition
- Clutter intensities and detectability estimates
- State estimates / covariances
- Existence probabilities
Radar tracking processing pipeline

- Several steps transform raw data to point measurements
- In addition to the radar data, this uses nautical charts
Detection performance analysis of radar tracking

How well are different track initiation methods performing?
Obstacle management interface

- Keep both obstacles currently being tracked, and obstacles whose tracks recently were terminated in the system.
- Use a decaying track-loss factor to gradually reduce the relevance of the latter kind.

Sudden changes in situational awareness when, e.g., a track is lost and reacquired, can lead a COLAV system to make dangerous actions.
## Overview of experiments

<table>
<thead>
<tr>
<th>When</th>
<th>Where</th>
<th>COLAV method</th>
<th>Data source</th>
<th>Ownship</th>
<th>Target ship</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2017</td>
<td>Near Munkholmen</td>
<td>DW</td>
<td>Radar</td>
<td>Telemetron</td>
<td>Motorboat of the Autosea students</td>
</tr>
<tr>
<td>May 2017</td>
<td>Near Munkholmen</td>
<td>SB-MPC</td>
<td>AIS</td>
<td>Telemetron</td>
<td>Munkholmen 2</td>
</tr>
<tr>
<td>Nov. 2017</td>
<td>Den Helder, NL</td>
<td>SB-MPC</td>
<td>AIS</td>
<td>Telemetron</td>
<td>RIB of Dutch navy ++</td>
</tr>
<tr>
<td>June 2019</td>
<td>Near Munkholmen</td>
<td>SB-MPC BC-MPC</td>
<td>AIS Radar</td>
<td>Telemetron</td>
<td>Munkholmen 2 FF Gunnerus</td>
</tr>
</tbody>
</table>
COLAV experiments May 2017: DW with Radar

- Telemetron (ownship) vs 17-foot motorboat
- COLAV based on radar tracking (PDAF) and Dynamic Window (DW).

⇒ Need a COLAV method that is less sensitive to velocity estimate fluctuations.
⇒ COLREGS compliance mandatory?
The Branching Course MPC method with radar tracking
Trondheimsfjorden, October 2017

Our first successful experiments with radar tracking.

- Sharp turn shows proaction in accordance with COLREGS Rule 8B.
- User interface demonstrates the transparency of the MPC approach.
- Collision avoidance method designed to handle fluctuating course estimates.
• Transition costs prevent wobbling.
• Behaviors close to the expectations of an experienced mariner.
• Can violate COLREGS if necessary.
Global, local reactive and proactive COLAV methods

- **Global methods**: Methods that come up with a path or trajectory for an entire mission.
- **Local methods**: Methods that come up with a temporary deviation from a desired path, and which aim to return to the path as soon as it is considered safe.
- **Proactive methods**: The ability to make and follow a plan according to situational awareness in a predictable manner.
- **Reactive methods**: Methods whose evasive control inputs depend directly on the state vector through a functional relationship, and other non-proactive methods.
- **Long-term methods**: Methods that aim to utilize a complete information picture.
- **Short-term methods**: Methods that utilize understanding of the vehicle dynamics to provide more sudden evasive maneuvers.
### Current and future research building on Autosea

<table>
<thead>
<tr>
<th>Multi-sensor fusion and fundamentals of tracking</th>
<th>Approaching the shore and harbors</th>
<th>Situational awareness for autonomous ships</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Fusion of EO cameras, IR cameras, radar and lidar</td>
<td>• Include shore constraints in COLAV methods</td>
<td>• Long-term vessel trajectory prediction</td>
</tr>
<tr>
<td>• Georeferencing for passive sensors</td>
<td>• Simultaneous localization and mapping (SLAM) vs. non-SLAM localization</td>
<td>• Fusion of AIS and exteroceptive sensors</td>
</tr>
<tr>
<td>• Detectability models for radar tracking</td>
<td>• Extended object tracking</td>
<td>• Pose estimation</td>
</tr>
<tr>
<td>• Random finite set (RFS) foundations for multi-target tracking methods</td>
<td><strong>Is this big object a ship or the shore-side?</strong></td>
<td>• Risk-based COLAV</td>
</tr>
</tbody>
</table>

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**Is this big object a ship or the shore-side?**

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[Image of a coastal view with ships and lights, likely related to the research discussed.]

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[NTNU AMOS logo: Centre for Autonomous Marine Operations and Systems]

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[www.ntnu.edu/amos]
Final remarks

• We have demonstrated autonomous maritime collision avoidance based on AIS and radar tracking in a variety of scenarios.
• We are moving towards scenarios where margins of safety are smaller and richer sensor information is needed.

Situational awareness for autonomous ships is perhaps more characterized by large numbers of possibilities, both for what can possibly happen and for what the ship can do, than similar systems for cars, airplanes or underwater vehicles.
Selected publications

- **Helgesen et al.:** “Sensor Combinations in Heterogeneous Multi-sensor Fusion for Maritime Target Tracking”, in *Proc. FUSION, Ottawa, Canada*, 2019.
Thank you for your attention!

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