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Problem description

Background

Multi-target tracking is a key ingredient in collision avidance system for autonomous vehicles. Multi-frame tracking methods are commonly acknowledged as gold standards for multi-target tracking. The purpose of this master thesis is to develop a complete multi-frame system for autonomous ships, based on sensor inputs from radar and the Automatic Identification System (AIS).

Proposed tasks

The following task are proposed for this thesis:

- Extend an integer-linear-programming (ILP) based tracking method with suitable algorithms for track initiation and track management
- Develop a framework for fusion between radar tracks and AIS tracks
- Develop alternatives to N-scan pruning in order to enhance the computational efficiency of the tracking method
- Implement the tracking system in Python and/or C++
- Test the tracking system on simulated data
- Test the tracking system with real data recorded with the Navico 4G broadband radar mounted on Telemetron

Autosea

This thesis is associated with the AUTOSEA project, which is collaborative research project between NTNU, DNV GL, Kongsberg Maritime and Maritime Robitics, focused on achieving world-leading competence and knowledge in the design and verification of methods and systems for sensor fusion and collision avoid- ance for ASVs. The project has access to supervision and physical test platforms through our industry partners.

Preface

The work presented in this thesis

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Trondheim, 2017-06-05

Abstract

The answer is 42

Sammendrag

Løysinga er 42.

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Glossary

VHF The frequency range between 30 and 300 MHz.

AUTOSEA A collaborative research and development project between NTNU AMOS and the Norwegian maritime industry with aim to attain world leading knowledge in design and verification of control systems for ASVs.

Cluster Set of targets which share measurements.

Clutter Noise in the form of false measurements where the amount is assumed Poisson distributed.

COLREGS Convention on the International Regulations for Preventing Collisions at Sea.

Gross tonnage A measurement of a ship's overall internal volume.

Measurement A point in the measurement space where something is detected.

NMEA Communication protocol used between electronic maritime equipment, based on RS-422.

Radar Acronym for Radio Detection And Ranging. A device that uses radio waves to measure distance and bearing to other objects.

RS-232 Serial single ended communication standard.

RS-422 Serial differential communication standard.

SOLAS The International Convention for the Safety of Life at Sea.

Solver A program that solves optimization problems.

Target An actual object which the system is trying to track.

Track forest A forest of track hypothesis trees.

Track hypothesis A new measurement inside the gate for an existing track.

Acronyms

P_D Probability of detection

AIS Automatic Identification System

ASV Autonomous Surface Vessel

CAS Collision Avoidance System

CPA Closest point of Approach

CSTDMA Carrier Sense Time Division Multiple Access

DNV GL Det Norske Veritas Germanischer Lloyd

ILP Integer Linear Programming

IMO International Maritime Organization

JPDAF Joint Probabilistic Data Association Filter

MHT Multi Hypothesis Tracking

MUNIN Maritime Unmanned Navigation through Intelligence in Networks

NTNU Norwegian University of Science and Technology

PDAF Probabilistic Data Association Filter

RADAR RAdio Detection And Ranging

RFS Random Finite Set

SAR Synthetic Aperture Radar

SOTDMA Self Organized Time Division Multiple Access

TDMA Time Division Multiple Access

TOMHT Track Oriented Multi Hypothesis Tracker

VHF Very High Frequency

VTS Vessel Traffic Service

Nomenclature

$\bar{\mathbf{x}}$	Predicted state
$\hat{\mathbf{x}}$	Filtered state
cNLLR	Cumulative Negative Log Likelihood Ratio
$\mathrm{NLLR}_{i,j}(k)$	Negative Log Likelihood Ratio for target j at time k for measurement i
$\bar{\boldsymbol{P}}$	Predicted state covariance
$\boldsymbol{\Gamma}$	Disturbance matrix
$\hat{\boldsymbol{P}}$	Filtered state covariance
$\boldsymbol{\Phi}$	State transition matrix
$\boldsymbol{H}$	State observation matrix
$\boldsymbol{K}$	Kalman gain
$\boldsymbol{Q}$	Process noise covariance matrix
$\boldsymbol{R}$	Measurement covariance matrix
$\boldsymbol{S}$	Residual covariance
$\hat{\mathbf{z}}_k$	Predicted measurement at time step k
$\boldsymbol{\nu}_k$	Weighted measurement innovation for time step k

$\boldsymbol{\tau}$	Binary vector where the selected track hypotheses are 1
$\tilde{\mathbf{y}}_k^i$	Measurement innovation for measurement i at time step k
$\mathbf{v}$	Observation noise
$\mathbf{w}$	Process noise
$\mathbf{x}$	State vector
$\mathbf{z}_k$	Measurement at time step k
i	Measurement index
j	Target index
k	Time index
l	Hypothesis index
M	Number of leaf nodes (track hypotheses in the track forest)
m_k	Number of measurements in scan k
ms	Millisecond
N	Number of scans to keep in track tree
N_1	Number of real measurements in cluster
N_2	Number of targets in cluster
t	Time
t_k	Time at time index

Chapter 1

Introduction

1.1 Motivation

Automation- and control technology have throughout the history been a crucial part of reliving humans from for instance dangerous, exhaustive, repetitive or boring work. Examples of this is automation and robotics in production facilities, remotely operated vehicles for working and exploring the deep sea and disarming explosives. The level of self control varies from remotely controlled to self sensing and planning without human interaction.

The early motivation for automation was probably, and in many situations still are, to improve speed, quality and consistency, which all tends to lead to better economics. With a still decreasing threshold for automating processes, more focus is applied on easing the burden on people, either by combining robotics and humans in the same operation, or fully automate the task. These jobs are typically repetitive, dangerous or both.

Although humans are capable of both self improving and easily adapting to new tasks, they will always have good and bad days, performing the same task slightly different or be bored and unfocused. These are all aspects that leads to inconsistency and errors, which may not be a problem in a production environment with quality inspections, though inconvenient, but can be fatal in critical applications.

There also exists several places where humans and automated system work together to exploit both strengths, for instance in aviation where the pilots are always present in the cockpit, but the autopilot are flying the plane most of the time. This gives the pilots freedom from a very static and repetitive task where a human error could have fatal consequences. This symbiosis is somewhat similar to the workload on the bridge of commercial vessels, where the autopilot steering the ship most of the time, while the crew is setting the course.

For vessels that do very repetitive routes and jobs, like ferries and short domestic cargo transport, the mental fatigue on the crew can be an issue. Because of the need for crew in emergency situations, customer service and ship maintenance, larger ferries would still need crew. They could however been steered by an automated system, which is never tired, bored, intoxicated or distracted in any other way. This is one of many applications for Autonomous Surface Vessels (ASVs).

The sensor and control system needed for safe automation of any vessel is large and complex, and requires several layers of fault barriers to preLloydvent system errors for spreading and the ability to self monitor its own performance. The control system would know its own position and desired position, it would have access to maps to make a route, a Collision Avoidance System (CAS) to deviate from its planned route to act in accordance with the rules at sea (COLREGS) based on real-time situation information from the sensors on the vessel.

For ASVs to be a viable alternative to human guided ships, the potential savings must be more than marginal, and the control system must be at least as safe as a human operated vessel. The state-of-the-art is not at this point yet, but recent initiatives by large corporations in development in ASVs and the regulation of a dedicated test area for ASVs in Trondheimsfjorden in Norway are just two examples on the direction this technology is headed.

The worlds first autonomous ferry might be between Ravnkloa and Vestre kanalkai in Trondheim. The Norwegian University of Science and Technology (NTNU) and Det Norske Veritas Germanischer Lloyd (DNV GL) are working on a collaborate project to develop a small autonomous battery powered passenger and bike-cycle ferry, as an alternative to a bride over a canal.

An indicator of the momentum autonomous surface vessels have is the Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project, which is a collaborate project between several European companies and research institutes, partially funded by the European Commission. The project aims at developing and verifying concept of autonomous vessels with remote control from onshore control stations.

This work is focused on the sensor fusion which generates a real time data stream into the control system, enabling situational awareness and the foundation for predictive CAS like [1], which also was a part of the AUTOSEA project.

1.2 Previous work

This work is based on a pre-master project executed autumn 2016 [2, url=true]. In this project, it was shown that several off-the-shelf Integer Linear Programming (ILP) solvers was capable of solving the data association optimization problem in a singe sensor Track Oriented Multi Hypothesis Tracker (TOMHT). It also showed that under good to moderate conditions, the performance return when increasing multi-scan window more than a relative low threshold, was very low.

1.3 Outline of the thesis

Chapter 2 provides an introduction to the sensor systems used in this work, as well as some of the different Multi Hypothesis Tracking (MHT) variants that exist. Chapter 4 presents an overview of the complete measurement-to-guidance system and an in-depth explanation of the fused radar and Automatic Identification System (AIS) TOMHT tracking system. Chapter 5 presents the different scenarios that are used in performance evaluation of the tracker. Chapter 6 presents the results of the simulated scenarios, and one real scenarios recorded with an ASV in Trondheim, Norway. A discussion of the results and evaluation of the performance with respect to safety at sea is presented in Chapter 7. Suggestion for future work is presented in Chapter 8, followed by a conclusion in Chapter 9.

Chapter 2

Theoretical Background

2.1 Radar

2.1.1 Overview

RAdio Detection And Ranging (RADAR) is a detection technology that uses radio waves to observe stationary and moving objects. A transmitter sends out radio waves and a receiver is waiting for reflected echo's from objects, the time the echo is delayed determines the distance to the object. The transmitter and receiver will in many situations be in the same location, can be both stationary and mobile and fixed or rotating orientation. Depending on frequency, a radar can observe solid objects like air-crafts, ships, terrain, road vehicles and less solid objects like people and weather formations.

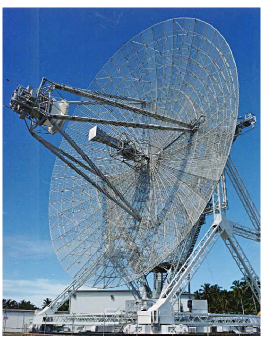

Figure 2.1: Fixed radar antenna

Figure 2.2: Rotating radar antenna

Figure 2.3: Maritime radar antenna

2.1.2 History

The fist implementation of an instrument that were able to detect the presence of distance metallic objects by radio waves was done by Christian Hülsmeyer in 1904. His invention did not measure the distance to objects, but whether there was an object in the direction of the instrument. The radar as we know it today was introduced in the mid to late 1930's, with world war two triggering a research to improve the still immature technology to be used in military applications. After the war, the technology matured and where put in use in several civil applications, where air traffic control, maritime safety and weather monitoring is the most common.

2.1.3 Principles

The electromagnetic waves that a radar emits travels at the speed of light in air and vacuum. It reflects back when there is a change in the density of the medium it is travelling through, which is what happens when radio waves hit targets. Electrically conductive materials tends to be good reflectors, since they have a very different atomic density than air. On the other hand, materials with poor conductivity, and also some magnetic materials, then to absorb radio waves good. Like light, there is many ways an incoming radio wave can be reflected, primarily dependent on the geometry of the target. A corner with angles less than 180° will reflect the incoming radio waves directly back to the sender, and is a good thing on targets that want to be visible on a radar. This principle are the basis for radar reflectors commonly used to boos the radar signature on smaller vessels, see Figure 2.4. The opposite is used on targets that try to minimize their radar signature, and is the reason why stealth vessels and aircraft are tiled by flat areas.

2.2 AIS

The Automatic Identification System (AIS) is a maritime safety and information system primarily designed for collision avoidance. AIS works by broadcasting messages

Figure 2.5: USS Zumwalt

Figure 2.6: KNM Gnist

Figure 2.7: F177 Nighthawk

on the Very High Frequency (VHF) band at irregular intervals with information on the vessels. AIS transceivers are required on international voyaging vessels over 300 gross tonnage, and on all passenger vessels. AIS signals are received at bother vessels and shore stations for use in Vessel Traffic Service (VTS) stations, open tracking databases like `www.marinetraffic.com`, fleet-monitoring and search and rescue. Since the AIS messages contains position, course and speed, AIS tracks can be overlaid on a map in a chart plotter or on top of a radar image, giving the operator two sensors to verify each other.

2.2.1 History

AIS was designed and developed by technical comities in the International Maritime Organization (IMO). Its objective was to enhance vessels safety and efficiency by increasing their ability to see and identify other vessels. The main motivation for adopting AIS was its independence of humans in operation, since it automatically identifies other vessels and displays the information on the navigational system on the bridge. It also enables automatic calculation of Closest point of Approach (CPA) and time until CPA, in which the navigation system could alarm the bridge on incoming traffic on dangerous course. This gives the navigator on the bridge more and better information for making decisions, but with the caveat that not all vessels have AIS. In the 2002 IMO SOLAS Agreement, it is required that vessels over 300 gross tonnage and all passenger vessels must be equipped with class A AIS transceivers. A simpler and cheaper AIS version named class B aimed at smaller vessels and yachts was published in 2006, followed by a large increase in the amount of non-commercial vessels equipped with AIS.

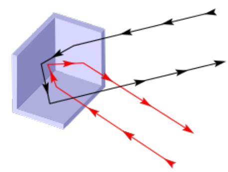

Figure 2.4: Corner reflector

Need citation

2.2.2 Messages

AIS broadcasts both static, dynamic and voyage information with varying intervals based on the vessels speed, status and on request from shore stations. Static, dynamic and voyage messages are listed in Table tables 2.1 to 2.3. When the AIS standard was developed, the peak traffic situations in the two most densely trafficked waterways, Singapore and Dover Straits, where used to calculate the update frequency for the AIS system. Based on these two locations and a desire to keep the number of reports per minute below 2000, the dynamic information report intervals for class A and B was set as in Table 2.4 and 2.5 respectively [3]. Static information is transmitted every 6 minutes, and on request from VTS stations. AIS transceivers are utilizing two reserved VHF channels; AIS 1 — 87B (161.975MHz) and AIS 2 — 88B (162.025MHz) to improve robustness against interference. An important note is that AIS transceivers are alternating which channel they are transmitting on, which means that if a receiver is only listening on one channel, the effective update rate halves.

2.2.3 Class A

Class A AIS transceivers are designed for Self Organized Time Division Multiple Access (SOTDMA) transmission, which is a way of reserving transmission time slot for the next broadcast. SOTDMA is based on Time Division Multiple Access (TDMA), with an extension allowing for self organizing of time slots compared to TDMAs dedicated timing manager. This effectively gives class A AIS transmissions priority over Class B equipment which may not have SOTDMA. Class A transceivers are also required to have build-in display, minimum transmission power of 12.5W, ability to filter targets and communication interfaces like RS-232 and NMEA.

2.2.4 Class B

Class B AIS transceivers are designed to be simpler and cheaper than Class A transceivers, which is accomplished through less strict requirements for hardware and operation. Class B AIS transmits at lower power, usually 2W and transmits at larger time intervals than Class A, see Table 2.5. It is not required to have a build-in display and can use both Carrier Sense Time Division Multiple Access (CSTDMA) and SOTDMA for transmission. CSTDMA is a simpler approach to time division than SOTDMA since it only listen for a single time slot to be unused before it transmits.

2.3 Tracking

2.3.1 Overview

Tracking, in this context, is to follow stationary and moving targets that are observed by a system without included association data. The problem is to know which measurements belong together over time, often refereed to as the data association problem.

Static AIS information	
MMSI	Maritime Mobile Service Identity
Call sign	Maritime radio (VHF) call sign
Name	Name of vessel
IMO Number	Vessel IMO number
Length and beam	
Location of positioning fixing antenna	
Height over keel	

Table 2.1: Static AIS information

Dynamic AIS information	
Position	In WGS84 frame
Position accuracy	Better or worse that 10 meter
Position time stamp	UTC in whole seconds
Course over ground (COG)	
Speed over ground (SOG)	
Heading	
Navigational status	
Rate of turn (ROT)	

Table 2.2: Dynamic AIS information

Voyage AIS information	
Draught	Depth in water
Hazardous cargo	Type
Destination	Name of place
Estimated time of arrival (ETA)	
Route plan / waypoints	
Number of persons on board	

Table 2.3: Voyage AIS information

Vessels status	Reporting Interval
Ship at anchor or moored and not moving faster than 3 knots	3 minutes
Ship at anchor or moored and moving faster than 3 knots	10 seconds
Ship 0–14 knots	10 seconds
Ship 0–14 knots and changing course	3.3 seconds
Ship 14–23 knots	6 seconds
Ship 14–23 knots and changing course	2 seconds
Ship > 23 knots	2 seconds
Ship > 23 knots and changing course	2 seconds

Table 2.4: Class A Reporting Intervals

Vessels status	Reporting Interval
Ship < 2 knots	3 minutes
Ship 2–14 knots	30 seconds
Ship 14–23 knots	15 seconds
Ship > 23 knots	5 seconds
Search and Rescue aircraft	10 seconds
Aids to navigation	3 minutes
AIS base station	10 seconds

Table 2.5: Class B Reporting Intervals

2.3.2 History

Tracking is a relative new filed of study, originating from the military technology race post 1945, enabled by the development of microprocessors and computers from the 60's. The applications ranged from sonar tracking on both submarines and navy vessels, to air control and missile guidance. This historical background is likely the reason for most published papers using these types of applications as background for testing. In recent years, tracking people and vehicles from visual- and Synthetic Aperture Radar (SAR) imagery have also become a topic in the research community [4]–[6]. There have also been published some research work on usage of tracking for ASVs [7], [8], although both are focused on interaction and response to external events.

There are several factors contributing to the challenge of good tracking;clutter, lower than unity Probability of detection (P_D), multiple detections of the same vessel and wakes. Clutter is a term for unwanted measurements or noise, which is inherent in every observation system. For a maritime radar, this can be caused by waves, rain, snow, birds or shore echo. A common assumption on clutter is to assume the amount being Poisson P_D is a measure of how persistent the target is in the measurements, and will vary much between different types of targets.

2.3.3 Single-target Tracking

The simplest approach to tracking is single-target tracking, where it is assumed that there are only one target in the measurement area, and any other measurement is regarded as either extra measurements of the target or false measurements, often referred to as clutter.

2.3.4 Multitarget tracking

A subset of tracking is multitarget tracking, where the problem expands to jointly estimate both the number of targets and their trajectories [9]. While a large number of tracking techniques have been developed, the three most used are Joint Probabilistic Data Association Filter (JPDAF), MHT and Random Finite Set (RFS) [9].

2.3.5 JPDAF

JPDAF is a multitarget expansion of Probabilistic Data Association Filter (PDAF) which is a single-target tracking technique. The essence of them both is consider

2.3.6 RFS

2.3.7 MHT

Chapter 3

Radar and AIS preprocessing

3.1 Radar processing

3.2 AIS processing

3.2.1 Out-of-order filtering

Chapter 4

MHT Module

4.1 Overview

4.2 Motion Model

4.3 Initiation

4.4 AIS updates

Assumptions: the AIS measurements are out-of-order filtered, ID-swap filtered and only the latest update from each target is passed through to the MHT tracking loop. These pre-processing steps are elaborated in ... All AIS updates are buffered from when they are received to the next radar scan. This is a design choice, which in some sense synchronize the AIS to the radar. Since the radar period is much smaller than (or in the best case for the AIS, equal to) the AIS transmit period, this will seldom lead to unused AIS measurements. On the other hand, since the radar period is relative short, the amount of time any AIS position will be predicted forward is typically small enough to not cause uncertainty larger than manageable for the algorithm. As will be obvious in Section 4.5.1, this prediction is only used for the gating sequence.

4.5 Hypothesis generation

4.5.1 Fusing two measurements

Since the AIS position (most likely) originates before the radar measurement, the fusion is carried out in two steps as a sequential update [10]

4.6 Clustering

4.7 Optimal data association

4.8 Dynamic window

4.9 N-Scan pruning

4.10 Track termination

Chapter 5

Simulations

5.1 Radar only

5.1.1 Large spacing and good conditions

5.1.2 Large spacing and challenging conditions

5.1.3 Small spacing and good conditions

5.1.4 Small spacing and challenging conditions

5.2 Radar and AIS

5.2.1 Large spacing and good conditions

5.2.2 Large spacing and challenging conditions

5.2.3 Small spacing and good conditions

5.2.4 Small spacing and challenging conditions

Chapter 6

Results

Resultater her.

Chapter 7

Discussion

Discussion here.

Chapter 8

Future work

Chapter 9

Conclusion

Conclusion here.

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