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Maritime piracy situation modelling with dynamic Bayesian networks

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ABSTRACT

A generative model for modelling maritime vessel behaviour is proposed. The model is a novel variant of the dynamic Bayesian network (DBN). The proposed DBN is in the form of a switching linear dynamic system (SLDS) that has been extended into a larger DBN. The application of synthetic data fabrication of maritime vessel behaviour is considered. Behaviour of various vessels in a maritime piracy situation is simulated. A means to integrate information from context based external factors that influence behaviour is provided. Simulated observations of the vessels kinematic states are generated. The generated data may be used for the purpose of developing and evaluating counter-piracy methods and algorithms. A novel methodology for evaluating and optimising behavioural models such as the proposed model is presented. The log-likelihood, cross entropy, Bayes factor and the Bhattacharyya distance measures are applied for evaluation. The results demonstrate that the generative model is able to model both spatial and temporal datasets.

1. Introduction

Real-world data of illegal activities such as maritime piracy and illegal immigration is scarce [1]. Furthermore, the maritime piracy data that does exist is considered incomplete. Some ship owners do not report pirate attacks in order to avoid insurance costs and lengthy investigations [2]. Real world data is often required for developing applications that counter such illegal activities. Applications may include automatic situation assessment and threat assessment methods. In the maritime piracy domain, an ideal threat assessment method should identify a vessel as a threat before a pirate attack occurs. This may be performed by utilising a model that describes the behaviour of pirate vessels in their prowling state. To form the model of pirate prowling behaviour, data of pirate vessels in this state is generally required. No such data has been found. This study proposes a generative model that is able to model behaviour and generate synthetic behavioural data.

A multi-agent generative model of a maritime piracy situation is proposed. The model consists of a novel variant of a dynamic Bayesian network (DBN) that extends the switching linear dynamical system (SLDS). The DBN is hybrid DBN that consists of both discrete and continuous variables. The structure of the DBN is informed by prior knowledge of the problem. Behaviour of various vessels in a maritime piracy situation is modelled by the DBN. The behaviour consists of various activities such as sailing, target acquisition, and attacking. The proposed DBN provides the capability to model a vessel at the level of the motion state vector. The model is provided with information such as the vessel class and various contextual elements. Synthetic data such as track data of a particular vessel being simulated is generated.

The proposed model is applied to generate a synthetic dataset of pirate attack locations. The model is evaluated by comparing the synthetic dataset to a real world dataset. The real world dataset consists of a set of locations of the pirate attacks that occurred in 2011. A novel method of evaluating and optimising the model is proposed. The evaluation is expressed as a likelihood that indicates the capability of the generative model to produce the real world dataset. An optimisation procedure is demonstrated for optimising the model parameters. The results indicate that the generative model has the ability to produce real-world-like data in terms of a statistical distribution. Cross validation is applied to evaluate how well the model generalises the 2011 pirate attack dataset. An evaluation using Bayes factor indicates that the proposed model performs well. The temporal modelling capability of the model is demonstrated. Pirate behaviour is modelled such that a particular temporal distribution of monthly pirate attacks is generated. This distribution is compared to temporal 2011 pirate attack data.

Over each simulation, unique results may be produced by the generative model. The desired statistical structure is maintained over each simulation. The ability to define unique results is ideal

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for generating data for algorithms such as machine learning algorithms.

The novelty of this work lies in the use of a SLDS in the DBN to generate simulated track data. No applications have been found in literature where the SLDS is extended into a DBN for providing a context based behavioural model. The proposed DBN provides a complete framework for synthetic data generation. A novel framework for evaluating behavioural models is presented. The proposed evaluation and optimisation method may easily be adapted to other problems. The purpose of this work is primarily for the testing of maritime pirate behaviour detection algorithms.

2. Background and related work

The DBN proposed in this study may be considered as a multi-agent system. Each vessel modelled by the DBN may be considered as an agent. Multi-agent systems have been applied in various fields. These include robotics, computer games, simulation, econometrics, military and social sciences [3,4]. Multi-agent Based Simulation (MABS) is a relatively new paradigm for modelling and simulating entities in an environment [5]. Agents are generally considered to be autonomous, independent and able to interact with their environment and other agents [5,6]. The military MABS is intended to enhance training and support decision making [7]. The application considered in this study may be argued to be a form of a military based MABS. A review of military based MABS applications are provided in [8].

The Bayesian network (BN) [9] is a directed graphical model. The BN exists in various forms that include the dynamic Bayesian network and the influence diagram. The DBN [10] is a temporal extension of the Bayesian network (BN) [9]. Applications of the DBN include computer vision based human motion analysis [11], situation awareness [12] and vehicle detection and tracking [13]. The influence diagram (ID) is a BN supplemented with decision variables and utility functions [14]. It could be argued that the higher levels of the DBN model presented in this study form an influence diagram. IDs been applied to solve a vast number of decision problems. Poropudas and Virtanen have used IDs in the analysis of simulation data [15]. Their work has been extended to include the use of DBNs for the application of simulation [16,17]. Time evolution is studied and what-if-analysis is performed. The simulation approach is applied to problems involving server queuing and simulated air combat. The structure of the DBNs are application specific and are not necessarily relevant to modelling maritime vessels in a pirate situation. The use of expert knowledge to construct the DBN is suggested as a possible extension to their work. In this study, prior knowledge is used to inform the structure of the DBN for modelling maritime vessel behaviour.

The SLDS [18–20] is a form of a DBN. In literature, various names are associated with the SLDS. These include the switching Kalman filter and the switching state space model [19]. The SLDS has been successfully applied to various problems that include human motion modelling in computer vision [21], econometrics [22] and speech recognition [23]. No attempts to use SLDS as a generative model for data synthesis have been found in literature.

This study is intended to fall within the framework of information fusion. The structure of the DBN is formulated to provide the means fuse information from various sources. A wide variety of maritime surveillance applications within the field of information fusion exist. A simulation test-bed has been developed for coastal surveillance [24]. The test-bed is developed for the study of distributed fusion, dynamic resource and network configuration management, and self synchronising units and agents. The BN has been used for information fusion for maritime security [25,26] and maritime domain awareness [27,28]. A DBN has been proposed for multi-sensor information fusion [29]. Data from various sensors such as imaging sensors, acoustic sensors and radar sensors may be fused using the DBN. A DBN has been applied for information fusion in a driver fatigue recognition system [30]. The DBN is a discrete based DBN that provides an indication of the level of fatigue of a driver. A hybrid DBN has been used for gesture recognition in human–computer interfaces [31]. The DBN may be argued to be in the form of an SLDS. In these applications, the DBN is used for recognition and detection. In this study, the DBN is used for simulation and data generation.

Context-based applications incorporate and model contextual information. The model proposed in this study provides a means to incorporate various external elements that influence behaviour. A survey of context modelling has been conducted by Strang and Linnhoff-Popien [32]. A more recent survey on context modelling and reasoning in pervasive computing has been conducted in [33]. Context-based information fusion has been applied to video indexing [34], computer vision [35] and natural language processing [36]. Context-based information fusion has found use in various maritime situation and threat assessment applications [37–39]. The DBN is not used in any of these applications. A DBN has been used in context based information fusion system for location estimation [40]. This system has been extended to include fuzzy logic for imprecise contextual reasoning [41,42]. As for information fusion applications, the DBN and BN are generally used for detection and recognition. The use of the DBN for synthetic data has not been found in literature.

Website applications for situation awareness have been made available. The model proposed in this study could be considered for deployment on a website based system. An on line data visualisation and risk assessment tool for maritime piracy is available [43]. The European Commission has developed the Blue Hub for maritime surveillance data gathering [44]. The platform is currently in development for maritime piracy awareness.

Maritime piracy is a problem of international concern. Maritime piracy poses humanitarian, economic and environmental risks [45]. In late 2008 three counter-piracy missions were deployed. These include the EU's Operation 'Atlanta', NATO's Operation 'Ocean Shield' and the US-led Combined Task Force-151 [46]. These operations have deployed war ships to patrol high risk regions and assist maritime piracy victims. Due to the vast patrol regions, patrolling efforts are partially successful. The use of technology is proposed to assist in combating maritime piracy [47]. In September 2011, an advanced study institute (ASI) was held in Salamanca, Spain to discuss the maritime piracy problem. The objective of the discussions was to help deter predict and recognise maritime piracy using information systems [48]. Topics such as information fusion methods, situation assessment methods, surveillance and challenges associated with the collaboration between information systems and humans were discussed. This study is intended to provide an information system that may be used in the counter-piracy endeavour.

This study considers the maritime piracy problem. Various applications have been proposed in literature for combating maritime piracy. Game theory has been used to optimise counter piracy strategies. Game theory has been utilised to suggest transport routes that avoid maritime pirates [49,50]. A game theoretic approach that seeks to optimise counter piracy patrolling strategies has been implemented [51]. Risk analysis has been used to assist ship owners and captains in managing risk during a pirate attack [52,53]. Methods for pirate detection have been discussed in literature. An approach to detect pirates through satellite communication monitoring has been proposed [54]. Other approaches intend to detect pirate vessels by classifying small craft in imagery [55,56].

A state based multi-agent simulation environment has been proposed for simulating maritime entity behaviour [1]. Long-haul