



**AFRL-AFOSR-UK-TR-2022-0049**

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Information-based distributed multi-sensor multi-target tracking

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**05/27/2022**  
**Final Technical Report**

**DISTRIBUTION A: Distribution approved for public release.**

Air Force Research Laboratory  
Air Force Office of Scientific Research  
European Office of Aerospace Research and Development  
Unit 4515 Box 14, APO AE 09421

## REPORT DOCUMENTATION PAGE

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<b>1. REPORT DATE</b> 20220527	<b>2. REPORT TYPE</b> Final	<b>3. DATES COVERED</b>	
		<b>START DATE</b> 20190315	<b>END DATE</b> 20220314
<b>4. TITLE AND SUBTITLE</b> Information-based distributed multi-sensor multi-target tracking			
<b>5a. CONTRACT NUMBER</b>	<b>5b. GRANT NUMBER</b> FA9550-19-1-7008	<b>5c. PROGRAM ELEMENT NUMBER</b> 61102F	
<b>5d. PROJECT NUMBER</b>	<b>5e. TASK NUMBER</b>	<b>5f. WORK UNIT NUMBER</b>	
<b>6. AUTHOR(S)</b> Daniel Clark			
<b>7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)</b> RASTREO LTD 272 BATH STREET GLASGOW, LANARKSHIRE G2 4JR GBR			<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>
<b>9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> EOARD UNIT 4515 APO AE 09421-4515		<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> AFRL/AFOSR IOE	<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> AFRL-AFOSR-UK-TR-2022-0049
<b>12. DISTRIBUTION/AVAILABILITY STATEMENT</b> A Distribution Unlimited: PB Public Release			
<b>13. SUPPLEMENTARY NOTES</b>			
<b>14. ABSTRACT</b> As shown in the attached final report this highly successful line of research met the objectives of the grant. <ul style="list-style-type: none"> <li>• Develop scalable solutions to multi-target tracking for large-scale systems.</li> <li>• Develop distributed solutions to multi-sensor fusion based on information-theoretic principles.</li> <li>• Determine how much information can be exchanged for multi-sensor multi-target tracking systems.</li> </ul> The advances in basic research supporting multi-object target tracking produced by the grant have resulted in 6 publications in peer reviewed scientific journals, two publications in peer reviewed conference proceedings, and three additional submitted manuscripts to peer reviewed journals under consideration for publication.			
<b>15. SUBJECT TERMS</b>			
<b>16. SECURITY CLASSIFICATION OF:</b>		<b>17. LIMITATION OF ABSTRACT</b>	<b>18. NUMBER OF PAGES</b>
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U	SAR 10
<b>19a. NAME OF RESPONSIBLE PERSON</b> MARK FRIEND			<b>19b. PHONE NUMBER (Include area code)</b> 314-235-6292

Final Report for EOARD Grant FA9550-19-1-7008  
“INFORMATION-BASED DISTRIBUTED MULTI-SENSOR MULTI-TARGET TRACKING”

**Date: 1<sup>st</sup> June 2022**

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Period of Performance: 3/14/2019 – 3/14/2022

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**Abstract:** Short summary of most important research results that explain why the work was done, what was accomplished, and how it pushed scientific frontiers or advanced the field. This summary will be used for archival purposes and will be added to a searchable DoD database.

The overall aim of the project was to investigate and develop novel strategies for autonomous sensor control for distributed multi-sensor multi-object systems based on information-theoretic principles through the following objectives:

- Develop scalable solutions to multi-target tracking for large-scale systems.
- Develop distributed solutions to multi-sensor fusion based on information-theoretic principles.
- Determine how much information can be exchanged for multi-sensor multi-target tracking systems.

The project developed fundamental solutions for multi-sensor multi-target tracking:

- *Large-scale tracking of many objects:* The scale of the problem is growing and thus solutions need to be scalable to tracking many objects requires algorithms that mitigate combinatorial complexity. Low-complexity solutions for multi-target tracking will be developed and tested in complex environments. A method was developed for robustly tracking large numbers of targets that is scalable in the number of targets and number of measurements, which enables millions of targets to be tracked.
- *Determining the information content of multi-sensor multi-target tracking systems:* In sensor networks with high-density information, bandwidth may be a constraint for multi-sensor multi-target tracking. This project derived results for determining the information content in networks of sensors used for multi-target tracking. It is anticipated that this will facilitate assessments about the efficiency and effectiveness of a sensing network balanced against the amount and frequency of data sent.
- *Distributed integration of data from multiple sensors:* Operators are required to make decisions based on information from multiple tracking systems to enhance the overall situational awareness. A new method of distributed multi-sensor multi-target tracking is developed for multi-sensor integration that mitigates against corruption from inaccurate or misleading data sources.
- *Assessment of threat in multi-target surveillance applications:* Large-scale tracking of many objects enables the identification of immediate threats. However, some threats may be more pertinent than others. A new formulation of adversarial risk was developed to provide situational awareness for operators to aid prioritization of sensing assets.
- *Performance bounds for multi-target tracking estimators:* The inverse of the Fisher information, known as the Cramer- Rao bound, provides a bound on the estimator of a parameter and is fundamental for statistical analysis. It provides a minimum achievable variance or covariance for a parameter. A Cramer-Rao bound was derived for point processes based on mathematical concepts from quantum field theory that generalizes the concept to

variables that have spatial variates.

**Introduction:** Include a summary of specific aims of the research and describe the importance and ultimate goal of the work.

The objective of this project was to develop the underpinning methods required for autonomous distributed sensor management and fusion in challenging multi-target environments. This involved the development of algorithms that are able to automatically track multiple targets, classify, and allocate resources based on information received from multiple platforms with data association uncertainty and high false-alarm rates. Building on recent developments by the investigator in multi-target tracking and distributed sensor fusion, the work programme developed methods that could enable autonomous sensor allocation in large-scale multi-sensor multi-target tracking applications based on information-theoretic criteria. This was achieved by re-evaluating the key tools in information theory applied to the challenges of multi-target surveillance based on point process theory, which is designed to accommodate uncertainty in the states of individual targets and the target number. The information-theoretic methods developed are applied to multi-sensor problems to enable decisions to be made on how to allocate sensor resources in addition to refining the knowledge of the scene. The tools developed will help reduce the labour-intensive burden of monitoring single sensor feeds, and enable adaptive decisions to be taken to optimise the operation of multi-modal networks and enhance the overall knowledge of the surveillance region. The focus on information-theoretic representations of multi-target tracking scenarios will enable verification of whether sensor feeds can be reliably fused, to avoid the potential of data corruption. The project delivered key advanced in intelligent sensing to enable the continuous and adaptive surveillance in dynamic environments. These will be scalable for large-scale tracking of many targets from multiple distributed sensors.

## RESEARCH HIGHLIGHTS

1. **THE CRAMER RAO BOUND FOR POINT PROCESSES** The Cramér Rao bound provides a minimum achievable variance or covariance for a parameter for a univariate or vector-valued parameter. Point processes often have parameters that are described by functions and the variance and covariance for point processes are themselves functions with spatial variates. Consequently, the usual formulation of the Cramér Rao bound in these contexts is not applicable. The second-order derivative of Kullback's inequality, which relates the Kullback-Leibler divergence to Cramér's rate function, provides a description of the Cramér Rao bound. Following this derivation, we develop a form of Cramér Rao bound for point processes and random measures derived from the second-order functional derivative of Kullback's inequality, which relates the Kullback-Leibler divergence to Cramér's rate functional for point processes and random measures. The approach makes use of a result for the effective action in quantum field theory and makes an analogy between the propagator and inverse propagator to the Fisher information and Cramér Rao bound respectively.

2. **MUTUAL INFORMATION FOR SENSOR NETWORKS** Methods for information-theoretic control for networks of sensors are of interest for enabling the development of autonomous sensor systems. In this paper we revisit the fundamentals of information theoretic-based control for multitarget systems and present a systematic approach for determining information-theoretic situational awareness based on mutual information for point processes. The extension to multi-sensor systems is developed using the concept of a broadcast channel from information theory. Analytic results are presented for linear- Gaussian systems which enable low complexity solutions for determining information from multiple sensors and consider a large number of potential sensor configurations. We discuss extensions of single-target methods to multi-target scenarios and present results in in simulations.

3. **LARGE-SCALE MULTI-TARGET TRACKING** Modern tracking problems require fast, scalable, and robust solutions for tracking multiple targets from noisy sensor data. In this article, an algorithm that has linear computational complexity with respect to the number of targets and measurements is presented. The method is based on the propagation of the first two factorial cumulants

of a point process. The algorithm is demonstrated for tracking a million targets in cluttered environments in the fastest time yet for any such solution.

4. **CONTROLLING MULTIPLE INTERCEPTORS TO A TARGET** - We consider the problem of guiding an unknown number of controllable interceptors to rendezvous with the same target at the same time. It is assumed that the all of the interceptors and the target are described by linear dynamics with Gaussian noise, though the theory presented does not preclude more general models. This extends the work of Athans to consider a scenario where the number of interceptors is unknown and time-varying. In particular, the focus is on the development of a stochastic multi-object guidance law for simultaneous rendezvous and interception.

5. **ESTIMATION OF RISK IN MULTI-TARGET SURVEILLANCE APPLICATIONS** – We developed methods for estimating a quantity of interest in the context of military impact assessment that we shall refer to as adversarial risk. We formulate the adversarial risk as a function of the multi-object state describing a group of weapons, and propose two approaches to estimate it using multi-object filters. The first, optimal, approach is tailored to filters for point processes, and produces the mean estimate of the adversarial risk and its variance. The second, naïve, approach is applicable to any filter producing point estimates of the multi-object state, yet it is not capable of equipping a risk estimate with an indicator of its quality. We develop an implementation of the optimal approach for a particular multi-object filter.

6. **A NEW METHOD FOR DISTRIBUTED MULTI-SENSOR MULTI-TARGET FUSION**  
Multi-target tracking systems typically provide sets of estimated target states as their output. It is challenging to be able to integrate these outputs as inputs to other tracking systems to gain a better picture of the area under surveillance since they do not conform to the standard observation model. Moreover, in cyclic distributed systems, there may be common information between state estimates that would mean that fused estimates may become overconfident and corrupt the system. In this paper we develop a Bayesian multi-target estimator based on the covariance intersection algorithm for multi-target track-to-track data fusion. The approach is integrated into a multitarget tracking algorithm and demonstrated in simulations. The approach is able to account for missed tracks and false tracks produced by another tracking system.

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**Experiment:** Description of the experiment(s)/theory and equipment or analyses.

### **1. LOW-COMPLEXITY LARGE-SCALE MULTI-TARGET TRACKING**

The problem of multi-sensor multi-target tracking is at its core a combinatorial assignment problem, i.e. how do we assign these measurements to targets to estimate the states of targets present? When dealing with many targets in computationally constrained environments, it becomes important to identify how the system can be approximated in a way that still retains reliable information. For instance, the PHD filter propagates the first-order moment of a point process which leads to very fast computational algorithm but is unstable in its estimate of the number of targets. A following work, known as the Cardinalized PHD filter extends the PHD filter to also include the probability distribution in the number of targets, though is slow to react to changes in target number and suffers from undesirable pathological behaviour when targets are not observed, which has been shown to be due to strong negative correlations introduced between targets. More recent work shows that propagating second-order information significantly enhances the estimate without a significant increase in complexity, and does not suffer from the same undesirable filter behaviour. Extending to many targets, eg. in wide area surveillance data from multiple, will require further approximations. An example of the compromises that can made to achieve this is to assume that there are no false alarms. It was shown that it was possible to track thousands of targets under this assumption with the CPHD filter, though this required consideration of each possible number of targets, and imposed an artificial cap. The newly-derived second-order PHD filter by Dr Clark's team requires no computation of the cardinality distribution, i.e. the discrete distribution in the number of targets, does not suffer from negative correlations, and does not require

the artificial imposition on the maximum number of targets. If the false alarm process is removed, it is possible to consider tracking thousands of targets with linear complexity in the number of targets. This progress in the multi-object filtering literature led to algorithms that compute the first-order moment of multiobject distributions based on sensor measurements. The number of targets in arbitrarily selected regions can be estimated using the first-order moment, as well as implementations providing cardinality information. Though these statistics provide important information about the number and location of targets, it does not provide information about the uncertainty of objects that can be localised to specific regions of interest. Dr Clark's team introduced explicit formulae for the computation of the second-order statistic on the target number. The proposed concept of regional variance quantifies the level of confidence on target number estimates in arbitrary regions and facilitates information-based decisions. Exploiting the concept of statistical moments for point process, the expression of the regional statistics for multi-object filters has been introduced by Dr Clark's team. Complementing the Probability Hypothesis Density (PHD) or first-order moment density of a multi-target point process, by providing the mean number of targets in any arbitrary region of the state space (e.g. the surroundings of a building of strategic importance), we have introduced the second-order moment measure of a multi-target point process, providing the variance in the estimated number of targets in any such region.

## **2. INFORMATION STATISTICS FOR MULTI-TARGET SYSTEMS**

One of the key motivations driving this work is to determine quantitative answers to the following question in sensor fusion applications: "If each object provides a piece of information, how much information is in that region that I don't already know?". It is believed that this relates to calculating the mutual information between the current state and the newly observed state. Information-theoretic concepts have been long explored in multi-sensor fusion, yet there is still work to be done to exploit all of the relevant information for multi-target tracking to direct sensors to regions of interest of the highest priority. The basic definition of entropy for multi-object estimation doesn't provide a complete answer to this, perhaps oddly, since there has been a lot of work on information theory since Gibbs' treatise. This is because in the multi-target scenario (i.e. with point processes) the basic definition of Shannon entropy gives the average entropy per object defined over the whole state space. In a multi-target tracking application, the operator is more interested in being able to make decisions based on a particular region of surveillance. Moreover, the average information per object may not be the most interesting quantity. It is more relevant to consider cumulative entropy, where each object contributes a piece of information. Such concepts can be explored in the context of point process theory, though have yet to be defined for this purpose. These would provide a basis for multi-sensor systems to determine autonomous decisions to be taken based on refined information localised to regions of interest. Let us suppose that we have developed such concepts and consider a multi-sensor fusion problem. If we consider a single platform, then we could compute the Shannon or Renyi entropy localised to a particular region and the cumulative entropy where each object gives a piece of information. If we consider a multi-platform configuration, then we can compute localised relative entropy for overlapping regions. Following this, we can compute the mutual information and conditional entropy to determine how much new information is in a particular region of interest. The development of these underlying information-theoretic descriptions will provide the basis for another important concept in information theory, which is yet to be explored in a multi-target context, namely Shannon's concept of the capacity of a channel. Once the fundamental concepts of mutual information have been applied to multi-object estimation, this leads the way to determining explicit solutions for channel capacity of individual sensors, and sensor networks.

## **3. NETWORK INFORMATION FOR A MULTI-SENSOR MULTI-TARGET SYSTEM**

A communication channel from Shannon's information theory relates to a system in which the output depends probabilistically on its input, and is characterised by a conditional probability distribution and the mutual information between the input and the output. The capacity of the channel determines the maximum amount of information that can be sent over a channel and be recovered within a tolerable error. Since the concept is built on the concepts of conditional probability and mutual information, it is reasonable to consider the generalisation to multi-object systems via their probabilistic representation with point processes. In particular, if one considers a point process conditioned on observations from a sensor, then with a suitable definition of mutual information, we can in theory determine the channel capacity of the sensor in terms of how many objects it can track. For instance, we could imagine that if the number of targets was so large that there was always a detection in every resolution cell on a radar,

then any output from the multi-target tracker would be useless. Investigation of this concept in terms of detection theory would enable the specification of the multi-target channel capacity of a sensor. Analogous concepts could then be explored in terms of networks of sensors to determine the capacity of a sensor network. This work would provide a fundamentally new concept for multi-target tracking systems.

#### **4. DISTRIBUTED DATA FUSION**

Distribution and decentralisation of fusion operations are key properties of network centric operations and distributed data fusion algorithms (DDF) have been developed to support them. These algorithms fuse data collected locally with state estimates propagated from other nodes. If the full advantages of NCOs are to be realised, these algorithms should exploit local information only: no single node, for example, should be an "oracle" which must maintain the entire state of the network. Although DDF introduces many advantages in terms of scalability, modularity and robustness, it does so at the cost of double counting. The estimates exchanged between nodes are not conditionally independent of one another because of common process noise (they are tracking the same target) and common observation noise (if estimates have been exchanged between nodes in the past). However, failure to account for this common information means that it is exploited multiple times. As a result, estimators become overly optimistic about the quality of their estimates, leading to inconsistency and even catastrophic failure.

The optimal solution to the double counting problem was developed by Chong, Mori and Chang (CMC) and uses the insight that estimates can be fused as long as the common information between them is divided out. Although this solution is optimal (in the sense that a distributed system can eventually converge to the same result as a single, centralised system) it requires the condition that the common information between all the nodes in the network can be computed at all times. For arbitrary network topologies, this can only be achieved if oracle nodes exist. This violates the assumptions of distribution and decentralisation and undermines much of the utility of DDF. However, in the special case of a tree connected topology, common information can be estimated through the use of channel filters that monitor the information sent on each communication link independently of all other link. However, channel filters only explicitly exploit the fact that, in a tree-connected topology a single path exists between any pair of nodes. Multiple links, which cause redundancy and hence robustness, introduce cycles which cause the channel filter approach to fail. Therefore, optimal DDF algorithms can only be used in networks which are fragile and contain no redundancy. However, these limitations arise from the attempt to implement the optimal CMC algorithm. Uhlmann argued that many of these could be overcome if suboptimal solutions were used and proposed a principled suboptimal algorithm known as Covariance Intersection (CI). CI has proved to be a very powerful and general method for fusing data in arbitrary networks and has been used in a range of distributed and other applications where full correlation structures cannot be maintained. However, CI only utilizes the mean and covariance of the estimates and cannot exploit any additional distribution information such as the number of modes. Hurley's generalisation of CI to general probability distributions replace the product form of Bayes Rule with an exponential mixture density (equivalently a weighted geometric mean). Theoretical and practical analysis has demonstrated that this generalisation has a sound theoretical basis.

**Results and Discussion:** Describe significant experimental and/or theoretical research advances or findings and their significance to the field and what work may be performed in the future as a follow on project. Fellow researchers will be interested to know what impact this research has on your particular field of science.

## RESULTS AND DISCUSSION

### INFORMATION STATISTICS FOR MULTI-TARGET TRACKING

The motivation for this work package is to determine a quantitative answer to the following question in multi-target tracking and sensor fusion applications: If each object provides a piece of information, how much information is over there? There have been approaches in the point process literature for addressing a similar problem though restricted to providing global information statistics such as the Kullback-Leibler and Renyi divergences. This work aims to provide a consistent approach for developing solutions that can be localised to particular regions and further summary statistics based on the number of objects. This work will extend some of the ideas recently introduced by Baccelli et al. for localised Shannon information for point processes, though directed to the specific objectives of multi-target surveillance. In particular, mathematical tools will be developed to provide information to operators based on assigning information to each object. The main developments will follow from fundamental concepts in information theory, such as entropy (Shannon and Renyi), as well as divergences (Kullback-Leibler and Renyi). We will explore the mathematical tools such as Golomb's information generating function within the context of point processes, and develop information-theoretic solutions for multi-object information. It is anticipated that this study will lead to principled descriptions of information that are tailored to multi-target surveillance, since the localisation of information will be of direct benefit to autonomous sensor allocation (eg. one can determine the most "interesting" region of interest).

## RESULTS AND DISCUSSION

1. The first key outcome was a new methodology for determining information statistics for point processes (*Local entropy statistics for point processes, published in IEEE Transactions on Information Theory 2020*). This provides a mechanism for determining quantitative statistics related to information and uncertainty localized to particular regions. This was developed with a view to enabling autonomous sensor decisions without the need for operators. This will be developed in the context of threat assessment in year 2 to enable decisions based on threat prioritisation.
2. The second key outcome was the development of a Cramér's Rao lower bound for point processes (*A Cramér Rao bound for point processes, published in IEEE Transactions on Information Theory*). This gives a lower bound on the variance of any unbiased point process estimator.
3. The third key outcome was a means of controlling an unknown number of interceptors for rendezvous with a moving target (*Stochastic Multi-Object Guidance Laws for Interception and Rendezvous Problems, published in IEEE Transactions on Automatic Control*).

## 2 LOW-COMPLEXITY MULTI-SENSOR MULTI-TARGET TRACKING

Multi-target tracking solutions with low computational complexity are required in order to address large-scale tracking problems. Solutions based on statistics determined from point processes, such as the PHD filter and CPHD filter are some examples of these algorithms. There are few solutions of linear complexity in the number of targets and number of measurements, with the PHD filter being one exception. However, the trade-off is that it is unable to propagate beyond first-order moment statistics. In a recent work by Clark and de Melo, a new filter was proposed with the same complexity as the PHD filter that also propagates second-order information via the second-order factorial cumulant. The new linear-complexity cumulant (LCC) multi-target filter has been derived and implemented that propagates second-order information in the target number. It is shown that the filter is more robust than the PHD filter while maintaining the same run-time. This is achieved by making a different approximation on the joint target-measurement process before applying Bayes' rule. Since there are very few linear-complexity solutions for multi-target tracking, the LCC filter is a promising solution for large-scale

multi-sensor multi-target tracking However, the extension to a multi-sensor environment for the LCC filter is yet to be considered. The investigation will evaluate the application of the LCC filter in a centralised multi-sensor context, as well as a distributed multi-sensor context. This will require the derivation of new point process models for multi-sensor multi-target tracking through the application of Bayes' rule and the multi-sensor multi-target generalization of covariance intersection, known as exponential mixture densities.

## **RESULTS AND DISCUSSION**

- The key outcome is a very low complexity multi-target tracker that is able to track a million targets in under a minute per iteration (*submitted to IEEE Transactions on Aerospace and Electronic Systems, July 2020*). Simulation results that it performs faster than the previous fastest algorithm, and is more accurate.

### **3. ADVERSARIAL RISK ASSESSMENT**

This work investigated the integration of a threat assessment procedure into the information-based multi-object statistics framework. Specifically, we address the situation where threat level characterises a population of objects. Filtering algorithms are commonly designed such as to only provide low-level information, such as number of objects, their locations and velocities, etc. They are not adapted to deliver higher level information related to threat assessment. In particular, this work is concerned with threat assessment in defence scenarios where some valuable asset has to be protected against an offensive operation carried out by multiple mobile threats. For example where stationary aircraft has to be defended from one or more swarms of explosive-filled drones. In our context we define threat as a population of objects who operate in the surroundings of the asset and whose predicted or estimated behaviour is likely to negatively affect the asset. For an isolated population, threat assessment naturally unfolds into a certain number of problems. First of all, it is necessary to uncover the configuration of a population, i.e. the number of objects and their physical states. Second, a level of threat, or significance, needs to be attached to this population. Threat level is an entity commonly used to prioritise response actions in a situation with multiple threats, e.g. allocating of sensing resources or weapon systems. Sensors such as radar will provide information about environment and will ultimately reveal the presence of objects. The information-based multi-object tools developed will be an ideal framework for processing sensor data, as it handles uncertainty in detections, missed detections and false alarms, and deliver observation results in probabilistic manner. In this work package we shall extend the information-based tools to incorporate threat level which will help refine autonomous decisions.

## **RESULTS AND DISCUSSION**

- The key outcome is new method for assessing risk to assets in a multi-target surveillance application (published in *IEEE Transactions Aerospace and Electronic Systems*, January 2021)

### **3. DISTRIBUTED DATA FUSION**

Distributed data fusion algorithms combine the state estimates that are generated by a number of fusion centres or nodes. However, the estimates from the different nodes are not conditionally independent of one another and, if optimal fusion is to occur, common information has to be cancelled out. However, in most networks computing this information is prohibitively expensive. An alternative is to use suboptimal fusion techniques. Covariance Intersection (CI) has proved to be a very powerful and general method for fusing data in arbitrary networks and has been used in a range of distributed and other applications where full correlation structures cannot be maintained. However, CI only utilizes the mean and covariance of the estimates and cannot exploit any additional distribution information such as the number of modes. A generalisation of CI to general probability distributions, replaces the product form of Bayes Rule with an exponential mixture density (equivalently a weighted geometric mean). In a recent work, the investigators develop a consistent approach for distributed multi-target tracking by combining a generalised version of Covariance Intersection, based on Exponential Mixture Densities (EMDs), with point processes. In a Dstl-sponsored project, the investigators developed this and demonstrated it on live radar and camera feed in trials with BAE Systems. The new linear-complexity

multi-target tracking algorithms developed by Clark potentially provide a new approach to low complexity multi-target tracking with second-order information.

## RESULTS AND DISCUSSION

- The key outcome is a new fusion method for distributed multi-target tracking that can be integrated into a range of multi-target trackers for utilising their track output (*Submitted to IEEE Transactions on Aerospace and Electronic Systems, 2021*).

## 4. NETWORK INFORMATION FOR A MULTI-SENSOR MULTI-TARGET SYSTEM

A communication channel from Shannon's information theory relates to a system in which the output depends probabilistically on its input, and is characterised by a conditional probability distribution and the mutual information between the input and the output. The capacity of the channel determines the maximum amount of information that can be sent over a channel and be recovered within a tolerable error. Since the concept is built on the concepts of conditional probability and mutual information, it is reasonable to consider the generalisation to multi-object systems via their probabilistic representation with point processes. In particular, if one considers a point process conditioned on observations from a sensor, then with a suitable definition of mutual information, we can in theory determine the channel capacity of the sensor in terms of how many objects it can track. For instance, we could imagine that if the number of targets was so large that there was always a detection in every resolution cell on a radar, then any output from the multi-target tracker would be useless. Investigation of this concept in terms of detection theory [ ] would enable the specification of the multi-target channel capacity of a sensor. Analogous concepts could then be explored in terms of networks of sensors to determine the capacity of a sensor network. This work would provide a fundamentally new concept for multi-target tracking systems.

## RESULTS AND DISCUSSION

- A systematic approach for determining multi-sensor mutual information for linear-Gaussian multi-target systems is presented. Using mutual information for the Kalman filter and conditional entropy for point processes, the paper derives the mutual information for common multi-target tracking models. Analytic equations are presented for stochastic control of a sensor for multi-target surveillance. Multi-sensor network information is developed based on broadcast channels from network information theory. In previous works on information based decision-making for multi-sensor multi-target tracking applications, the number of potential sensor choices has been limited due to the computational complexity of the solutions. Since the approach taken in this work provides low-cost solutions, we are able to gain much better situational awareness of information content. Simulation studies indicate that maximization of information globally may not provide the best approach to sensor management since it can be multimodal across the parameter space. (published in *IEEE Transactions on Signal Processing*)

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## FOLLOW-ON PROJECTS

[fo1] D. E. Clark, *Network information-theoretic sensor management for multi-target surveillance*, Centre Interdisciplinaire d'Etudes pour la Défense et la Sécurité, Institut Polytechnique de Paris, Agence de l'innovation de défense, Ministère des Armées, France

The objective of this proposal is to develop an approach to adaptively allocate sensing resources in multisensor multi-target tracking surveillance networks based on fundamental concepts in network information theory and decision-theoretic criteria.

[fo2] D. E. Clark, *Fundamental performance bounds for stochastic decision-making in multi-sensor multi-target tracking networks*, AFOSR

The development of reliable autonomous decision-making in sensor networks requires robust methods of assessing the output of surveillance systems and determining actions without human intervention. This is particularly crucial for large-scale multi-sensor systems where the involvement of an operator to make the decision on how to allocate resources is infeasible. The objective of this proposal is to develop key performance measures for assessment and analysis of multi-sensor multi-target tracking systems. The result of these developments will inform the development of a new robust class of information-based sensor-scheduling algorithms to enable intelligent autonomous decision-making in large-scale sensor networks. The focus is on the development of basic tools in estimation theory that are fundamental for statistical analysis applied to the specific challenges of multi-target surveillance where there is uncertainty in the number of objects and the object states. These developments will inform the assessment of scalable large-scale tracking systems from many distributed sensors to meet the particular challenges of space surveillance applications which require methods for managing large-scale sensor networks for tracking tens of thousands of objects in orbit.

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**List of Publications and Significant Collaborations that resulted from your EOARD supported project:** In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

a) papers published in peer-reviewed journals,

[a1] D. E. Clark, "Stochastic Multi-object Guidance Laws for Interception and Rendezvous Problems," in *IEEE Transactions on Automatic Control*, vol. 67, no. 3, pp. 1482-1489, March 2022, doi: 10.1109/TAC.2021.3062559.

[a2] D. E. Clark, "A Cramér Rao Bound for Point Processes," in *IEEE Transactions on Information Theory*, vol. 68, no. 4, pp. 2147-2155, April 2022, doi: 10.1109/TIT.2022.3140374.

[a3] A. Narykov, E. Delande and D. E. Clark, "A Formulation of the Adversarial Risk for Multiobject Filtering," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 57, no. 4, pp. 2082-2092, Aug. 2021, doi: 10.1109/TAES.2021.3098130.

[a4] M. A. Campbell, D. E. Clark and F. de Melo, "An Algorithm for Large-Scale Multitarget Tracking and Parameter Estimation," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 57, no. 4, pp. 2053-2066, Aug. 2021, doi: 10.1109/TAES.2021.3098155.

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c) papers published in non-peer-reviewed journals and conference proceedings,

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[c2] Clark, Daniel; Campbell, Mark (2022): Integrating Covariance Intersection into Bayesian multi-target tracking filters. *TechRxiv. Preprint*. <https://doi.org/10.36227/techrxiv.19351931.v1>

d) conference presentations without papers,

[d1] Flavio De Melo, Daniel Clark and Yohan Petetin: *A low-cost second-order multi-object tracking filter for WAMI surveillance, PGMODAYS 2021*

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e) manuscripts submitted but not yet published,

[e1] Clark, Daniel (2022): Kullback’s inequality and Cramer Rao bounds for point process models. *Submitted to IEEE Transactions on Signal Processing, 2022*

[e2] Clark, Daniel; Campbell, Mark (2022): Integrating Covariance Intersection into Bayesian multi-target tracking filters. *Submitted to IEEE Transactions on Aerospace and Electronic Systems 2021*

[e3] Daniel E. Clark, Emily Hunter, Bhashyam Balaji, Sean O’Rourke, Centralized multi-sensor multi-target data fusion with tracks as measurements, *Submitted to SPIE Defense and Security Symposium 2023*

f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

[f1] Daniel E. Clark, Emily Hunter, Bhashyam Balaji, Sean O’Rourke, Centralized multi-sensor multi-target data fusion with tracks as measurements, *Submitted to SPIE Defense and Security Symposium 2023*