ISIF Perspectives

On Information Fusion

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AN OPEN-SOURCE FRAMEWORK FOR TRACKING AND STATE ESTIMATION

THE 20TH-YEAR SPECIAL PROGRAM OF FUSION 2017

STATE AND TRAJECTORY ESTIMATION USING ACCUMULATED STATE DENSITIES

Publication of the
INTERNATIONAL SOCIETY OF INFORMATION FUSION

ISIF

ISIF Perspectives

Perspectives seeks bridging articles, expository papers and tutorials, classroom notes, and announcements on topics of general interest to the ISIF Fusion community. Fresh points of view on established topics are especially welcome, as are articles on topics of interest to the ISIF annual fusion conference. Papers containing new research should be directed to JAIF or other research journal. The standing Call for Papers (CfP) for ***Perspectives*** can be found at http://isif.org/sites/isif.org/files/CfP%20for%20Perspectives.pdf. The CfP for Fusion 2019 http://fusion2016.org/Call_For_Papers includes the topics (1) Theory and Representation, (2) Algorithms, (3) Modeling, simulation and evaluation, and (4) Applications.

Papers should be submitted online at http://isif.org/publications/isif-perspectives-information-fusion. The average length for submissions is approximately six (6) pages (in JAIF two-column format). All submissions will be reviewed for content and style, as well as suitability for ***Perspectives***. All papers accepted for publication will be written in a relaxed, colloquial style that facilitates understanding by a wide audience. Articles containing significant original research should be submitted to JAIF.

Cover: A collage intended to depict the synergy that can happen spontaneously with collaborative focused activity. The words are drawn from papers submitted over the last 20 years to FUSION conferences by authors from the corresponding continents; it was designed by Prof. Deqiang Han and the Information Fusion Research Group at Xi'an Jiaotong University, China. The "Stone Soup" image was provided by Dr. Paul Thomas of Dstl, UK, and was inspired by an ancient European folk tale whose moral concerns the value of sharing. Both images appear in the feature articles in this issue of Perspectives. The background is inspired by a poetic definition of information fusion due to Prof. Ning Zheng, Hangzhou Dianzi University, China; see the West Lake Workshop Report.

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IEEE Advancing Technology for Humanity · AESS · ISIF · UNIVERSITÄT BONN · Fraunhofer FKIE · HENSOLDT Detect and Protect. · DIEHL Defence

Call for Papers
13th Symposium on Sensor Data Fusion: Trends, Solutions and Applications

Motivation

To a degree never known before, human decision makers or decision making systems have access to a vast amount of data. Therefore, real-time data streams must not overwhelm the actors involved. On the contrary, the data are to be fused to high-quality information to provide a reliable decision support. Being a challenging exploitation technology at the common interface between sensors, command & control systems, data and information fusion has a large potential for future security and ISR systems in defence and civilian applications.

Scope

Sensor Data Fusion techniques provide higher-level information by spatio-temporal data integration, the exploitation of redundant and complementary information, and the available context. Important applications exist in logistics, advanced driver assistance systems, medical care, public security, defence, aerospace, rotbotics, industrial production, precision agriculture, traffic monitoring, sensor positioning and resource management.

Plenary Talk

Fusion Theory for Positive Noise by Fredrik Gustafsson

Key Aspects

- Distributed sensor fusion in complex scenarios
- Fusion of heterogeneous sensor information
- Exploitation of non-sensor context knowledge
- Artificial Intelligence of autonomous systems
- Risk analysis / data driven sensor management
- For the student registration a proof of the student's status is required
- One registration covers one paper only

Fees

€ 149.-	Students
€ 299.-	AESS Members
€ 349.-	IEEE Members
€ 399.-	Regular

Contributions

Prospective authors are encouraged to submit high-quality full draft papers (4-6 pages, IEEE format). All submissions are subject to a peer-review process by the technical program committee. Accepted and presented papers will be submitted to IEEE for publication. At least one of the authors of each accepted contribution is expected to register for the Symposium, which will be held in Bonn, Germany, and to present the paper. For details contact www.fkie.fraunhofer.de/sdf2019.

Important Dates

21 July 2019 Submission of full draft papers
07 Sept 2019 Notification of acceptance
15 Sept 2019 Submission of the final version
15 Oct 2019 Start of SDF 2019

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PERSPECTIVES MAGAZINE

Welcome to the second issue of *Perspectives Magazine*. Perhaps you recall that the first issue appeared in July 2016 and have noticed the long interval between issues—it was much longer than anticipated when the first issue appeared. New endeavors very often encounter special startup problems, and *Perspectives* is no exception in this regard. Rather than enumerate the problems, and there were quite a few, I would rather speak of two important changes that will make issues of our magazine more frequent.

The role of Editor-in-Chief for *Perspectives Magazine* is a volunteer position, like nearly all Editorial roles in professional technical societies. The job is rewarding in many ways, yes, and it requires—in addition to time and effort—that attention be devoted to it on a regular basis. To keep up the steady push needed to move *Perspectives* forward, I decided to share the burden by adding an Associate Editor-in-Chief. Dr. Jason Williams has joined *Perspectives Magazine* in this role. He brings a point of view that contributes to the international character that ISIF supports, and he has contributed much to making the second issue happen. I trust that all of ISIF will welcome him in this new role.

Another important step forward was recognizing the practical consequences of making *Perspectives* a magazine. It has many different kinds of articles with different writing styles and formats, and different review requirements as well. No issue is complete until every Department has at least one article. It is the duty of a magazine's Production Manager (PM) to work with the Technical Editors to seek papers that supply missing content. The final task of a PM is to assemble the issue from its parts to ensure that it has the desired look and feel when seen whole. *Perspectives* does not have a PM, but it certainly needs one. And now we do! It is my great pleasure to announce that Kristy Virostek of Conference Catalysts is assuming this role of PM beginning in 2019. Welcome aboard, Kristy!

This issue brings to you the broad cross-section of article types for which we aim. The first feature describes the excellent effort chronicling the longitudinal development of the Fusion community, presented at the twentieth FUSION conference in Xi'an in 2017. The second outlines an exciting project which aims to influence the future of the Fusion community, through bringing together a critical mass of data sets, evaluation methods and algorithms in an open source framework. Another article focuses on celebrating achievements in the Fusion community; you will find the history of FUSION conference awards, and articles announcing the latest FUSION conference awards, and ISIF awards.

A production like this is made possible by the contributions of authors, unnamed reviewers, and associate editors. Thank you, one and all, for the time and effort you gave to making this issue of *Perspectives Magazine* a reality.

Roy Streit
Editor-in-Chief

The 20th-Year Special Program of FUSION 2017

Abstract—This article is a report of the 20th-year special program of the 2017 International Conference of Information Fusion (FUSION 2017). The program presented various data about the past 20 FUSION conferences, including useful statistics (top rankings, research area trends, word cloud, etc.), important facts (e.g., best paper awards, organizing teams, plenary talks, sponsors, and obituaries), and special awards.

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INTRODUCTION

The International Conferences on Information Fusion (FUSION) are the flagship conferences in the area of information fusion. The first FUSION conference took place in 1998. FUSION 2017, held in Xi'an, China, was sponsored by the International Society of Information Fusion (ISIF), in association with Xi'an Jiaotong University, and technically co-sponsored by the Institute of Electrical and Electronics Engineers (IEEE), the IEEE Aerospace and Electronic Systems Society (IEEE-AESS), and the Chinese Information Fusion Society. It was the first FUSION conference in China.

As the 20th FUSION conference, FUSION 2017 included a special anniversary program. The program presented various data about the past 20 FUSION conferences in the following three classes:

a. Useful statistics drawn from the FUSION conferences in the past 20 years;

b. Special awards, in recognition of people and institutions who have contributed most to the FUSION conferences in various ways; and

c. Important facts about the FUSION conferences in the past 20 years.

All the above items were obtained based on the past FUSION conferences' proceedings and official websites.

X. Rong Li proposed the 20th-year special program to present facts, statistics, and special awards of past FUSION conferences. Deqiang Han was in charge of collecting facts and computing statistics. He was helped greatly by a team of graduate students in the Center for Information Engineering Science Research (CIESR), Xi'an Jiaotong University. Important decisions involved were made collectively by the program team: Zhansheng Duan, Yongxin Gao, Deqiang Han, Jian Lan, X. Rong Li, and Roy Streit.

To obtain the facts and statistics is hard and tedious work. First, we must have all previous conference proceedings. Since early proceedings were available only in hard copies and were hard to obtain, our team reached out to friends and received their great help. For example, Dr. Chee-Yee Chong scanned the proceedings of FUSION 1998 (the first FUSION conference) and sent us the electronic version. After all 20 years' proceedings were collected, the title, abstract, and keywords of each paper were extracted manually to generate the word clouds and area trends. Likewise, authors' information (names and affiliations) was extracted manually to obtain the "top rankings." We are grateful to the dozens of graduate students at CIESR, Xi'an Jiaotong University. Without their diligent work on data extraction and preparation, among others, it is impossible for the program to succeed.

USEFUL STATISTICS DRAWN FROM FUSION CONFERENCES IN PAST 20 YEARS

TOP RANKINGS IN PAST 20 YEARS

Top rankings in past 20 years of FUSION conferences are shown in Tables 1–8.

Table 1

People Who Attended Most (>15) FUSION Conferences

Name	Number of Attendances
Yaakov Bar-Shalom	20
Chee-Yee Chong	20
Jean Dezert	20
Elisa Shahbazian	20
X. Rong Li	19
Shozo Mori	19
Thiaglingam Kirubarajan	18
Roy L. Streit	17
William Dale Blair	16
Erik P. Blasch	16
Nageswara S. V. Rao	16
Johan Schubert	16

Table 2

People Who Have Most (>50) FUSION Papers	
Name	**Number of Papers**
X. Rong Li	153
Uwe D. Hanebeck	106
Erik Blasch	99
Chongzhao Han	96
Peter Willett	74
Jean Dezert	71
Fredrik Gustafsson	57

Table 3

Institutions Whose Members Have Most FUSION Papers	
Institution	**Number of Papers**
Xi'an Jiaotong University, China	188
University of New Orleans, USA	167
Karlsruhe Institute of Technology (including KIT and Universitat Kalsruhe), Germany	126
University of Connecticut, USA	119
ONERA, France	116
Air Force Research Lab, USA	113
Fraunhofer, Germany	97
Linkoping University, Sweden	90
Defence Science and Technology Organization, Australia	88
Northwestern Polytechnical University, China	88
George Mason University, USA	86
Swedish Defence Research Agency, Sweden	68

Table 4

People Who Organized Most Special Sessions	
Name	**Number of Sessions**
Uwe D. Hanebeck	35
Marcus Baum	10
Jesus Garcia Herrero	10
Wolfgang Koch	10
Igor Gilitschenski	8
Jose M. Molina	8
Javier Bajo	7
Erik Blasch	7
Florian Faion	7
Fredrik Gustafsson	7
James Llinas	7
Lyudmila Mihaylova	7
Benjamin Noack	7
Lauro Snidaro	7
Peter Willett	7

Table 5

People Who Made Most Service Contributions (Alphabetical List)							
Name	**General Chair**	**Executive Chair**	**Steering Chair**	**Program Chair**	**TPC Chair**	**TPC Member**	**Other Chair**
YaakovBar-Shalom	1	0	1	0	0	13	2
Dale Blair	0	0	1	0	0	6	3
Erik Blasch	0	0	0	1	1	16	2
Chee-Yee Chong	1	0	0	1	0	13	5
Stefano Coraluppi	1	0	0	1	2	8	0
Fredrik Gustafsson	0	0	0	0	2	12	1
Uwe D. Hanebeck	1	0	0	0	2	9	1
Wolfgang Koch	1	1	0	0	0	13	1
X. Rong Li	2	0	1	0	0	11	1
Mahendra Mallick	0	0	0	0	2	15	1
Elisa Shahbazian	0	0	0	1	2	9	1
Roy L. Streit	2	0	0	0	1	9	2
Peter Willet	1	1	0	0	1	11	3

Table 6

People Who Taught Most Tutorials	
Speaker	**Number of Tutorials**
Yaakov Bar-Shalom	13
Erik Blasch	12
Subrata Das	11
Thia Kirubarajan	10
Vesselin P. Jilkov	9
Wolfgang Koch	9
X. Rong Li	9
Roy L. Streit	9
Mieczyslaw M. Kokar	8
Jean Dezert	7
Audun Josang	7
Ronald Mahler	6
Galina Rogova	6

Table 7

Top 12 Institutions in Awards (Alphabetical List)							
Inst.	**Best Paper Award**	**1st Runner-Up (R)**	**2nd Runner-Up (R)**	**Best Student Paper Awards**	**1st Runner-Up (S)**	**2nd Runner-Up (S)**	**Nominees**
Chalmers Univ. of Tech., Sweden	1	1	—	—	—	—	—
DSTO, Australia	2	—	2	—	—	—	—
FKIE, Germany	2	—	—	1	—	—	—
KIT, Germany	2	—	—	1	2	—	2
Nanyang Tech. Univ., Singapore	—	1	1	—	—	—	—
Selex, Italy	—	—	1	1	—	—	1
Syracuse Univ., USA	1	—	—	1	—	—	—
THALES, Netherlands	1	—	—	—	—	—	1
Univ. College London, UK	1	—	—	—	2	—	1
Univ. of California, USA	1	—	—	—	—	—	1
Univ. of Connecticut, USA	2	1	—	1	1	2	3
University of New Orleans, USA	—	1	2	—	—	—	5

Table 8

Countries with Most FUSION Papers	
Country	**Number of Papers**
USA	1,983
China	639
France	501
Germany	475
Australia	377
Canada	319
UK	292
Sweden	267
Italy	177
Spain	135
All Countries	4,981

AREA TRENDS IN INFORMATION FUSION

Taking the opportunity that the 20th anniversary offered and advantage of China's great man power, the program did the information fusion community a service by providing some useful statistics about fusion research. The most valuable such statistics that can be obtained objectively is probably research trends of various areas in information fusion.

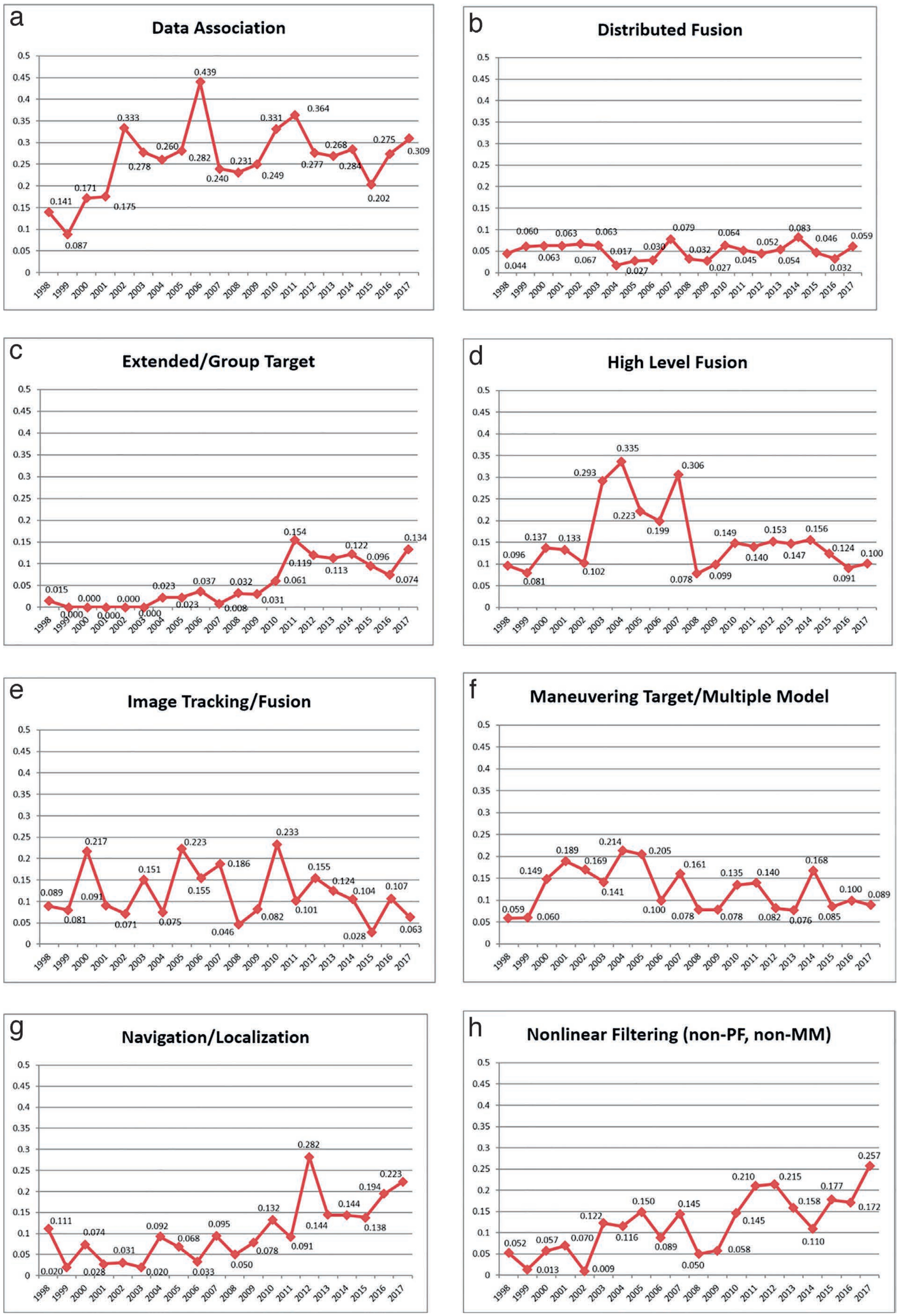
To show trends, topical areas of information fusion must be identified first to represent and cover information fusion research so far. After extensive discussions, our team settled on the following 14 areas: data association, distributed fusion, extended/group target, high level fusion, image tracking/fusion, maneuvering target/multiple model, navigation/localization, nonlinear filtering, particle filtering, random finite set, recognition/classification/detection, sensor management, sensor registration, and uncertainty modeling/reasoning.

Following the principle that the statistics should (a) be as objective as possible, (b) show time trend of each area, and (c) allow meaningful comparisons between areas, the team decided to use the same number (finally settled at six) of key words (phrases) to represent each area and show their relative occurrences to indicate trends.

Specifically, each area is represented by six keywords. They are the six most frequent phrases—of those suggested for the area by a set of active researchers in the area—in the titles, abstracts, and index terms of all FUSION conference papers in 20 years. A point on a curve is the total number of occurrences of the six keywords in the titles, abstracts, and index terms of the FUSION papers, divided by the total number of FUSION papers, in that year.

For example, if FUSION 1998 has 100 papers, then a value of 0.15 for 1998 for an area means that the six keywords appeared 15 times in total in the titles, abstracts, and index terms of the 100 papers.

Trends of 14 different topical areas are illustrated in Figures 1a–1n.


a
Data Association
0.141 0.087 0.171 0.175 0.333 0.278 0.260 0.282 0.439 0.240 0.231 0.249 0.331 0.364 0.277 0.268 0.284 0.202 0.275 0.309
b
Distributed Fusion
0.044 0.060 0.063 0.063 0.067 0.063 0.017 0.027 0.030 0.079 0.032 0.027 0.064 0.045 0.052 0.054 0.083 0.046 0.032 0.059
c
Extended/Group Target
0.015 0.000 0.000 0.000 0.000 0.000 0.023 0.023 0.037 0.008 0.032 0.031 0.061 0.154 0.119 0.113 0.122 0.096 0.074 0.134
d
High Level Fusion
0.096 0.081 0.137 0.133 0.102 0.293 0.335 0.223 0.199 0.306 0.078 0.099 0.149 0.140 0.153 0.147 0.156 0.124 0.091 0.100
e
Image Tracking/Fusion
0.089 0.081 0.217 0.091 0.071 0.151 0.075 0.223 0.155 0.186 0.046 0.082 0.233 0.101 0.155 0.124 0.104 0.028 0.107 0.063
f
Maneuvering Target/Multiple Model
0.059 0.060 0.149 0.189 0.169 0.141 0.214 0.205 0.100 0.161 0.078 0.078 0.135 0.140 0.082 0.076 0.168 0.085 0.100 0.089
g
Navigation/Localization
0.111 0.020 0.074 0.028 0.031 0.020 0.092 0.068 0.033 0.095 0.050 0.078 0.132 0.091 0.282 0.144 0.144 0.138 0.194 0.223
h
Nonlinear Filtering (non-PF, non-MM)
0.052 0.013 0.057 0.070 0.009 0.122 0.116 0.150 0.089 0.145 0.050 0.058 0.145 0.210 0.215 0.158 0.110 0.177 0.172 0.257
1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017

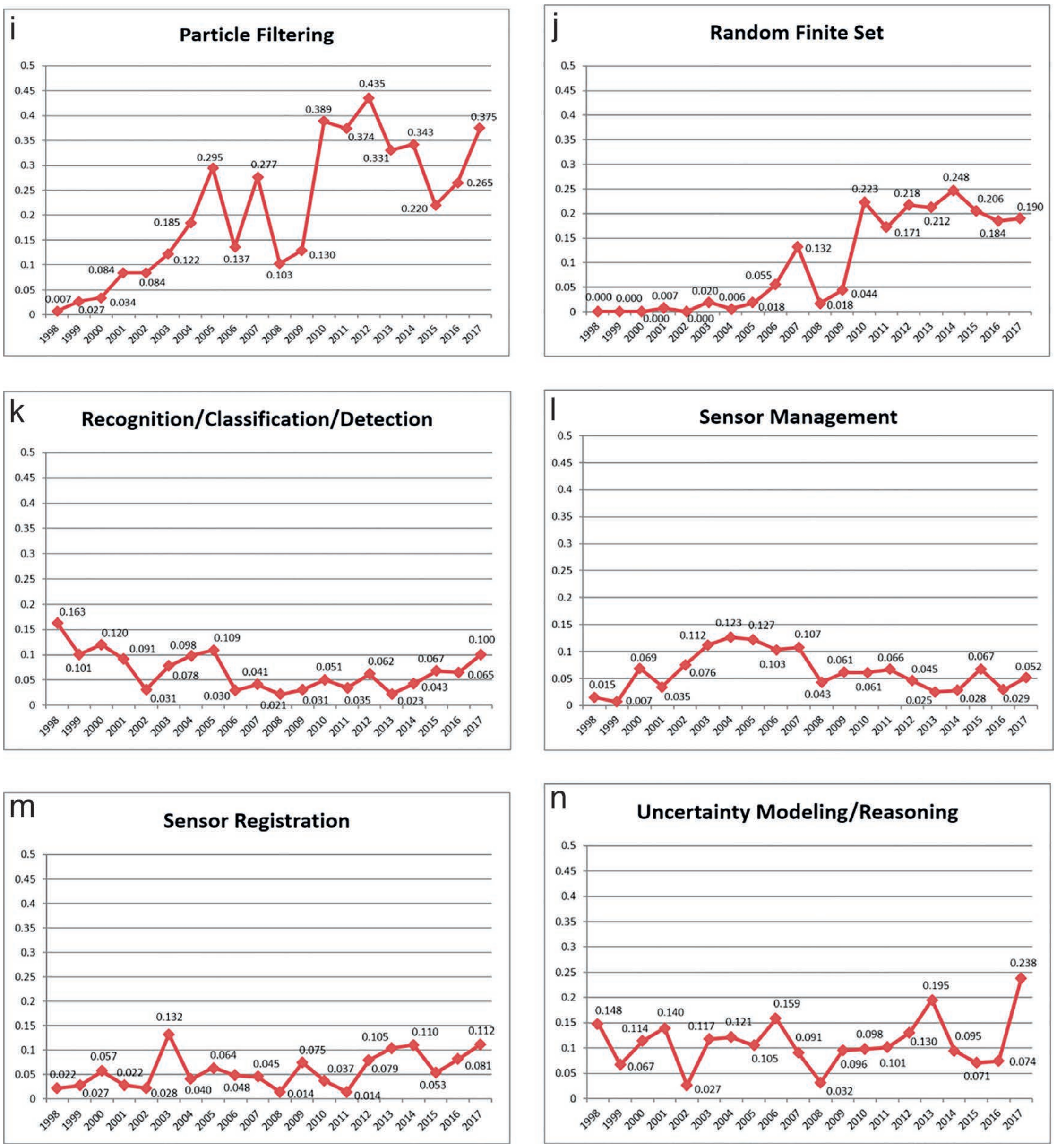


Figure 1

Area trends. (a) Data Association. Keywords: probabilistic data association/PDA, data association, multiple hypothesis tracker/tracking/MHT, probabilistic multiple hypotheses tracking/PMHT, joint probabilistic data association/JPDA, track-to-track association. (b) Distributed Fusion. Keywords: estimation/estimate fusion, decentralized fusion, distributed filtering, track fusion, tracklet fusion, track-to-track fusion. (c) Extended/Group Target. Keywords: extended object/target, object/target orientation, object/target extent, random matrix, group target, star convex. (d) High Level Fusion. Keywords: ontology, situation awareness, situation assessment, threat assessment, semantic, knowledge representation. (e) Image Tracking/Fusion. Keywords: image tracking, image fusion, video tracking, camera, image registration, mean shift. (f) Maneuvering Target/Multiple Model. Keywords: multiple model, motion model, maneuvering target tracking, hybrid system, interacting multiple model/IMM, maneuver detection. (g) Navigation/Localization. Keywords: GPS, satellite, time difference of arrival/TDOA, inertial navigation, time of arrival/TOA, positioning. (h) Nonlinear Filtering. Keywords: extended Kalman filter/EKF, unscented Kalman filter/UKF, nonlinear filter/nonlinear filter, multiple hypothesis tracking, Gaussian filter, density estimation. (i) Particle Filtering. Keywords: particle filter/PF, sequential Monte Carlo/SMC, MCMC, importance sampling, proposal distribution, sample impoverishment. (j) Random Finite Set (RFS). Keywords: PHD filter, probability hypothesis density, multi-Bernoulli, random finite set/RFS, GLMB/generalized labeled multi-Bernoulli, finite set statistics. (k) Recognition/Classification/Detection. Keywords: target detection, Support Vector Machine, pattern recognition, target recognition, object recognition, target classification. (l) Sensor Management. Keywords: sensor management, sensor resource management, sensor deploy, threat-based sensor management, sensor scheduling, resource management. (m) Sensor Registration. Keywords: simultaneous localization and mapping/SLAM, calibration, image registration, sensor bias, sensor registration, maximum likelihood registration/MLR. (n) Uncertainty Modeling/Reasoning. Keywords: fuzzy, Dempster-Shafer, belief function, evidence theory, basic belief assignment, membership function.

Figure 2

Word clouds of past 20 FUSION conferences. (a) 1998, (b) 1999, (c) 2000, (d) 2001, (e) 2002, (f) 2003, (g) 2004, (h) 2005, (i) 2006, (j) 2007, (k) 2008, (l) 2009, (m) 2010, (n) 2011, (o) 2012, (p) 2013, (q) 2014, (r) 2015, (s) 2016, (t) 2017, (u) 1998–2017.

Figure 2
Continued

From these trend curves, several significant observations can be made:

- The most popular areas are: particle filtering, data association, nonlinear filtering, random finite set, and uncertainty modeling/reasoning;
- Research efforts in data association, distributed fusion, image tracking/fusion, maneuvering target/multiple model, sensor registration, and uncertainty modeling/reasoning appear to stay steady, but those in image tracking/fusion may be dropping slightly in recent years;
- Extended/group target, navigation/localization, nonlinear filtering, particle filtering, and random finite set have received ever more attention;
- Attention to random finite set had a sudden rise about ten years ago, but it became steady in recent years. Likewise, for particle filtering and extended/group target in a lesser degree;
- Research efforts in high level fusion had a most noticeable high plateau during 2004–2008; and
- Attention to recognition/classification/detection exhibits a V-shaped curve.

These trend statistics are for reference only. They are based on FUSION conference papers in the past 20 years, which do not reflect fusion research trends completely.

WORD CLOUDS

A word cloud is a graphical representation of word frequency. To show the research focus or hot spots in each year's FUSION conference, the program generated word cloud figures based on all 20 years' conference proceedings (i.e., title, abstract, keywords of each paper).

The shape of each word cloud reflects the map of the hosting country. For example, the first FUSION conference took place in Las Vegas, Nevada, USA. So, its word cloud has a shape of the US map. Since the 20th FUSION was in China, its word cloud has a shape of the China map. We also provide a word cloud for the 20 years cumulatively in a shape of the world map. All these word cloud maps are shown in Figures 2a–2u.

As is clear from the word clouds, the hottest words are: tracking, fusion, data, sensor, target, estimation, model, filter, information, etc.

SPECIAL AWARDS

In recognition of people who have contributed most to the FUSION conferences in various ways, the program presented a number of special awards. They are as follows:

ISIF CONFERENCE ATTENDANCE AWARDS (FOR ATTENDING ALL 20 FUSION CONFERENCES FROM 1998 TO 2017)

These awards were presented to (alphabetically listed):

- Yaakov Bar-Shalom, University of Connecticut, USA
- Chee-Yee Chong, Independent Consultant, USA
- Jean Dezert, ONERA, France
- Elisa Shahbazian, OODA Technologies Inc., Canada

ISIF CONFERENCE ATTENDANCE AWARDS (FOR ATTENDING 16 OR MORE FUSION CONFERENCES FROM 1998 TO 2017)

These awards were presented to:

- X. Rong Li, University of New Orleans, USA (19 conferences)
- Shozo Mori, Systems and Technology Research, USA (19 conferences)
- Thiaglingam Kirubarajan, McMaster University, Canada (18 conferences)
- Roy Streit, Metron, USA (17 conferences)
- William Dale Blair, Georgia Institute of Technology, USA (16 conferences)
- Erik P. Blasch, Air Force Research Lab, USA (16 conferences)
- Nageswara S. V. Rao, Oak Ridge National Laboratory, USA (16 conferences)
- Johan Schubert, KTH Royal Institute of Technology, Sweden (16 conferences)

ISIF CONFERENCE TECHNICAL CONTRIBUTIONS AWARD (FOR CONTRIBUTING THE MOST FUSION CONFERENCE PAPERS FROM 1998 TO 2017)

This award was presented to:

- X. Rong Li, University of New Orleans, USA (153 papers)

ISIF CONFERENCE TECHNICAL CONTRIBUTION AWARDS (FOR CONTRIBUTING 50 OR MORE FUSION CONFERENCE PAPERS FROM 1998 TO 2017)

These awards were presented to:

- Uwe D. Hanebeck, Karlsruhe Institute of Technology (KIT), Germany (106 papers)
- Erik P. Blasch, Air Force Research Lab, USA (99 papers)
- Chongzhao Han, Xi'an Jiaotong University, China (96 papers)
- Peter Willett, University of Connecticut, USA (74 papers)
- Jean Dezert, ONERA, France (71 papers)
- Fredrik Gustafsson, Linköping University, Sweden (57 papers)

ISIF CONFERENCE SERVICE AWARDS (FOR CONTRIBUTIONS TO FUSION CONFERENCE ORGANIZATIONS DURING THE PERIOD FROM 1998 TO 2017)

These awards were given to (alphabetically listed):

- Yaakov Bar-Shalom, University of Connecticut, USA
- William D Blair, Georgia Institute of Technology, USA
- Erik P. Blasch, Air Force Research Lab, USA
- Chee-Yee Chong, Independent Consultant, USA
- Stefano Coraluppi, Systems and Technology Research, USA
- Fredrik Gustafsson, Linköping University, Sweden
- Uwe D. Hanebeck, Karlsruhe Institute of Technology (KIT), Germany
- Wolfgang Koch, Fraunhofer Institute for Communication, Germany
- X. Rong Li, University of New Orleans, USA
- Mahendra Mallick, Independent Consultant, USA
- Elisa Shahbazian, OODA Technologies Inc., Canada
- Roy Streit, Metron, USA
- Peter Willett, University of Connecticut, USA

IMPORTANT FACTS ABOUT FUSION CONFERENCES FROM THE PAST 20 YEARS

The program also collected and reported several important facts, including:

- Organizing teams (1998–2017)
  See FUSION 2017 official website details (http://isif.org/events/conference/fusion-2017).
- Plenary talks (1998–2017)
  See FUSION 2017 official website for details.
- ISIF presidents (1998–2017)
  See FUSION 2017 official website for details.
- Best paper awards and best student paper awards
  See article on page 45 and FUSION 2017 official website for details.
- Obituaries
  FUSION 2017 also memorialized the following deceased people in the FUSION research and engineering community:
  - Oliver Drummond, 1928–2016
  - David Lee Hall, 1946–2015
  - Otto Kessler, 1942–2015
  - Bob Lynch, 1960–2015
  - Jean-Pierre Le Cadre, 1953–2009
  - Darko Musicki, 1957–2014
  - Miroslav Simandl, 1954–2015
  - Pierre Valin, 1949–2014

  See FUSION 2017 official website for details.
- Sponsors (1998–2017)
  See FUSION 2017 official website for details.
- Host cities (1998–2017)
  See Figure 3.

Figure 3
Sitemap of past FUSION conferences.

Figure 4
Posters for useful statistics.

Figure 5
Posters for word clouds.

During the FUSION 2017 conference, all the above useful statistics, word clouds, and research trends were presented to the attendees by posters at the conference venue (Figures 4 and 5). Dr. X. Rong Li also presented a selection of data at the beginning of a plenary session (Figure 6).

POSTSCRIPT

All the above facts, statistics, and awards were presented and posted at FUSION 2017 and are available at the FUSION 2017 official website (http://isif.org/events/conference/fusion-2017).

We are grateful to the organizing committee, past organizers who helped us greatly, ISIF Board of Directors, all volunteers and everyone for their contributions to a successful FUSION 2017 and a memorable 20th-year special program.

Figure 6
X. Rong Li presented a selection of data at the beginning of a plenary session.

Stone Soup: An Open-Source Framework for Tracking and State Estimation

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***Abstract*—**The ability to detect and unambiguously follow all moving entities in a state space is important in many domains both in defense (e.g., air surveillance, maritime situational awareness, and ground moving target indication) and the civil sphere (e.g., astronomy, biology, epidemiology, and dispersion modeling). However, tracking and state estimation researchers and practitioners have difficulties recreating state-of-the-art algorithms to benchmark their own work. Furthermore, system developers need to assess which algorithms meet operational requirements objectively and exhaustively rather than driven by intuition or individual preference. We have, therefore, set up a collaborative initiative to create an open-source framework for production, demonstration, and evaluation of tracking and state estimation algorithms. Stone Soup is designed to be a (MIT–licensed) software framework for researchers and practitioners to test, verify, and benchmark a variety of multisensor and multiobject state estimation algorithms. The initiative is supported by four defense laboratories (Defence Research and Development Canada, Defence Science and Technology Laboratory, Defence Science and Technology Group, and Naval Research Laboratory), who are contributing to the development effort for the framework through the Technical Cooperation Program. The tracking and state estimation community will derive significant benefits from this work, including access to repositories of verified and validated tracking and state estimation algorithms, a framework for the evaluation of multiple algorithms, standardization of interfaces, and access to challenging data sets.[1]

"The fundamental requirement of Stone Soup is to enable the comparison of different algorithmic approaches against the same data or simulated scenario. Thus, algorithms must be interchangeable at the state and measurement model level."

INTRODUCTION

Imagine the scene: you are in a conference listening to a paper on a new approach to tracking or state estimation. The work looks impressive, and the author has shown good results on standard data sets. Using the conference Wi-Fi, you download the algorithm and reproduce the tests on your laptop while listening to the paper. Before the end of the session, you have applied the new algorithm to your data with your own metrics and compared it to your own work!

Does this sound far-fetched? As any researcher or practitioner knows, it is currently difficult and time consuming to recreate state-of-the-art algorithms to benchmark one's own work. Comparison of new algorithms with existing solutions involves recoding the alternative algorithms from the academic literature. Industrial users of algorithms also find it difficult to assess which algorithms meet requirements objectively and exhaustively rather than driven by intuition or personal favorites.

However, we see a solution to these issues in the open-source paradigm [1], [2], [3] that encourages coding in the open and exposure of an algorithmic source code. To this end, a consortium of government laboratories has started a project to develop an open-source tracking and state estimation framework suitable for populations with open-source (MIT-licensed[2]) com-

[2] https://opensource.org/licenses/MIT.

ponents. The project described in this article aims to provide a flexible and unified software platform for researchers and engineers to test, verify, and benchmark a variety of existing multisensor and multiobject estimation algorithms. It will also allow rapid prototyping of new algorithms in three language sets (Python, MATLAB, and C/C++), by providing a set of libraries that implement the necessary functions for tracking and state estimation. Note that the project is not intending to mandate a uniform "straightjacket"; instead, we would like to develop a modular repository of algorithms along with some convenient and popular frameworks for using those components.

STONE SOUP

The project, titled "Stone Soup," has six component types [4]: framework, data, algorithms, metrics, simulators, and sensor models (see Figure 1). The framework is the core of the project. This is the software infrastructure necessary to construct appropriate combinations of components from a repository. The framework is designed to mirror the mathematics in the components and be extensible to incorporate new algorithms developed by the research community, as well as data sets from different fields of interest, thus providing the ability to evaluate new algorithms on different problems more efficiently.

Evaluation takes place via the (interchangeable) metric module. Algorithms can also be evaluated against simulations that are generated by the interchangeable simulator module. The framework will also include an interface to the detector, which is the component that transforms raw data into discretized detections. These are likely to exist as external components, for example, open-source computer vision libraries for target detection from imagery, with a Stone Soup–compatible interface.

Components are logically connected by the data flow diagram in Figure 2. This illustrates how algo-

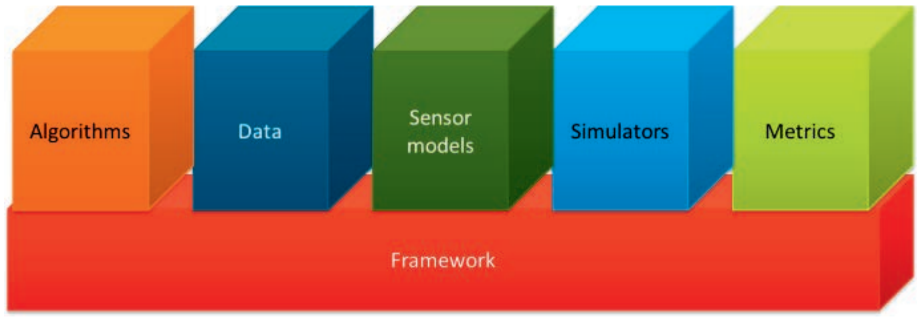

Figure 1
The components of Stone Soup.

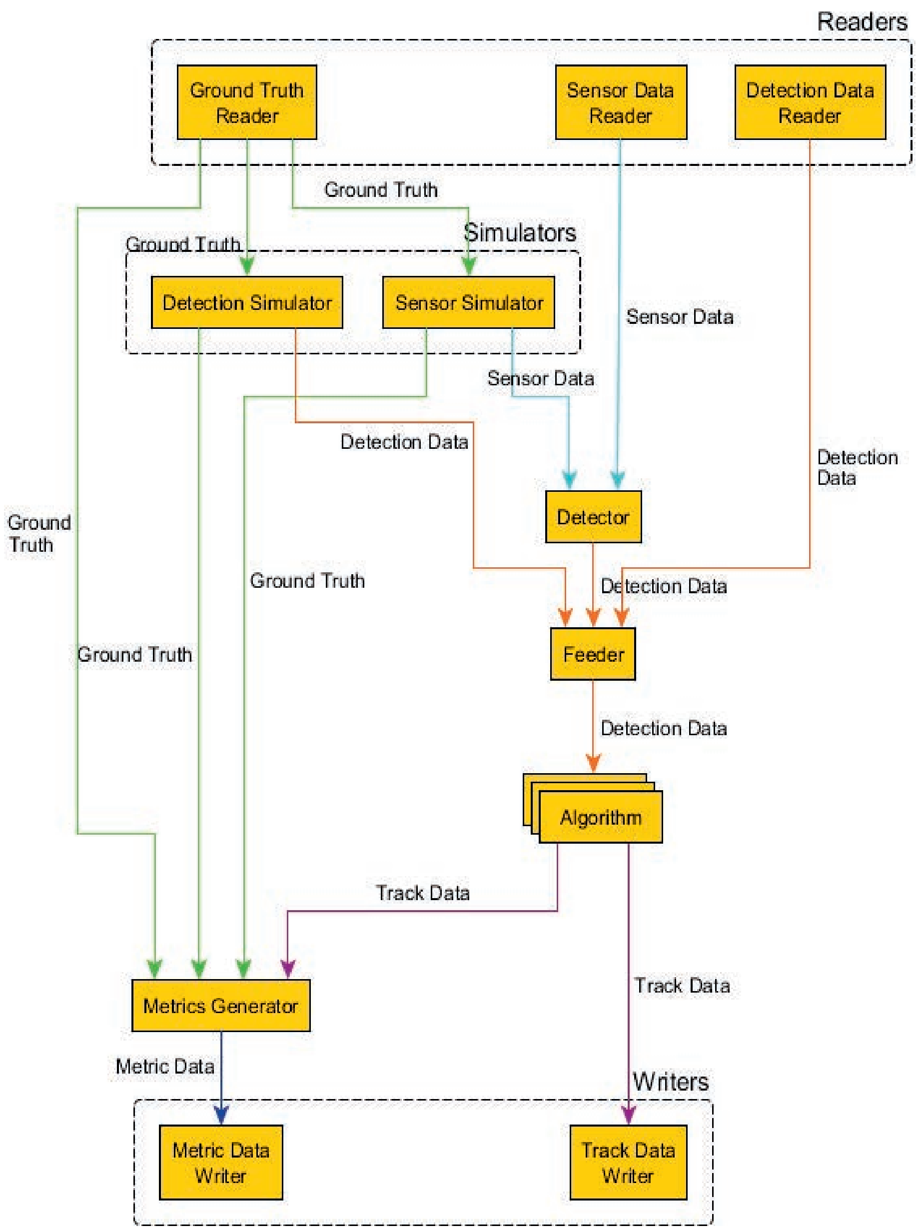

Figure 2
One possible example of a logical data flow that can be configured in Stone Soup.

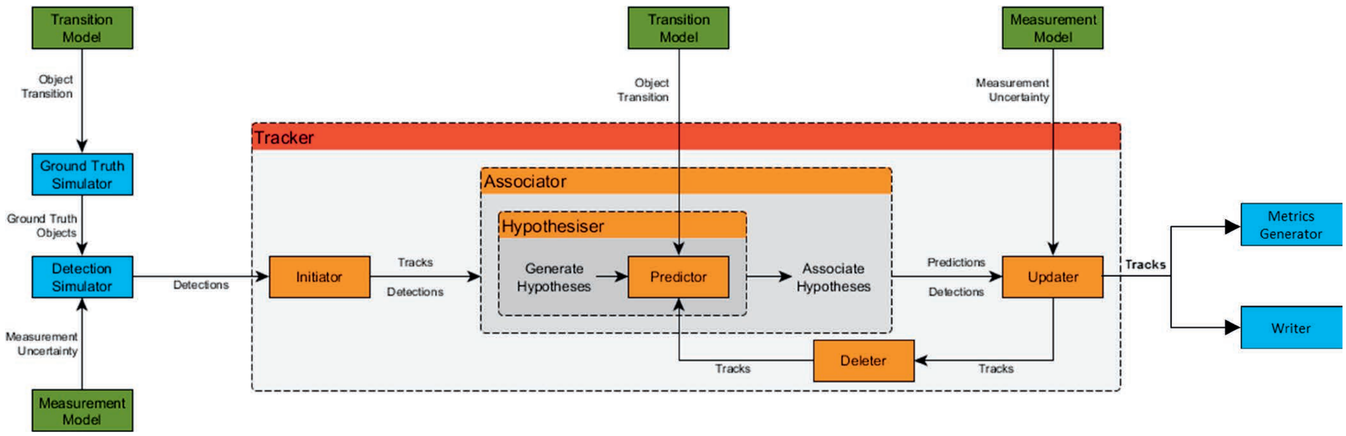

Figure 3
Simple tracker implementation.

rithms are fed with detection data and output track data. However, algorithms are not treated as monolithic code blocks in Stone Soup. Subcomponents of the algorithm can be interchanged for other functionally equivalent approaches. A simple tracker is shown in Figure 3. This makes a very powerful engine that can be used to understand exactly what part of a proposed algorithm is driving its performance. This is achieved by constructing a standard interface between subcomponents, using inheritance where necessary, such that the calling routine is agnostic to the approach within the code block. The framework is coded in Python.[3] Python's class-based, object-oriented, duck-typed[4] paradigm elegantly enables this approach. The interface that will allow MATLAB and C/C++ algorithms to be called from the Python framework is currently being developed and will be published in advance of the beta release.

The Stone Soup development team is working toward a beta release[5] of the software in April 2019 on a public repository of GitHub. A recent code sprint at the University of Liverpool is shown in Figure 4. The beta release will contain a set of basic Kalman filter– and particle filter–based algorithms, but future aspirations include things such as scalable multitarget track before detect, parameter estimation, support for parallel particle filtering, and support for real-time interfacing. We hope that these and many other research topics will be advanced by the open community with this framework. Indeed, we expect that contributions to future International Society for Information Fusion (ISIF) fusion conferences and the *Journal of Advances in Information Fusion* would, by default, produce algorithms in a Stone Soup–compliant format for exposure and use standard Stone Soup data sets and scenarios for comparisons. Although this represents the desired steady state, for accelerated development, the team hopes to integrate selected components drawn from the Tracker Component Library [5], published on GitHub. Similarly, Stone Soup would be released with an initial collection of data from the contributing government laboratories, with the desired aim that all parties who collect relevant data would contribute in the future.

Figure 4
A recent Stone Soup code sprint at the University of Liverpool.

ACCESSIBILITY

The key to wide adoption of this framework is to make it as accessible as possible. Most of the code developed up to the beta release of the Stone Soup project will be released under the MIT license, which is one of the most permissive forms of an open-source license. After beta release, others will be able to contribute additional components under any "permissive license"[6] (with the MIT license preferred), and existing components may be modified under their original license.

DEVELOPMENT PRIORITIES

Open-source software, unlike the traditional software development model, tends to develop amorphously according to the

[3] See www.python.org.
[4] https://en.wikipedia.org/wiki/Duck_typing.
[5] See https://en.wikipedia.org/wiki/Software_release_life_cycle.
[6] https://en.wikipedia.org/wiki/Permissive_software_licence.

will and enthusiasm of members of the user/developer community. However, to rapidly build the initial framework in the consortium phase, it is useful to have a set of development priorities. These priorities relate to compatibility with specified classes of algorithm and types of data and models that might be added in the open phase, rather than requiring specific functions to be added immediately.

DATA

Priority for the initial phases of Stone Soup will be to enable the use of the following data types. This involves the creation of an appropriate data model in the framework for handling the data and making available representative data sets in the repository. The initial data types will be:

- Airborne radar detection data, which can be two dimensional or three dimensional, from a rotating radar or from a planar array;
- Coincident automatic identification system data;
- Astrodynamic data (electro-optical [EO]): satellites against a star background; and
- Detections of ground targets in airborne EO and infrared data.

The intent is to build wider compatibility with further data types and provide more example data sets as the project progresses.

ALGORITHMS

Priority for the initial phases of Stone Soup will be to ensure compatibility with the following generic algorithm types:

- Filtering algorithms: discrete-time state and measurement models
  - Standard Kalman filter for the linear state and measurement model
  - Extended Kalman filter
  - Derivative-free Kalman filters
- Particle filter class of algorithms, e.g.,
  - Sequential Monte Carlo
  - Variations in sampling strategy (sampling importance resampling, sequential importance sampling, and auxiliary particle filter)
  - Rao–Blackwellized particle filter
- Multiple model filtering algorithms for Kalman filter class of algorithms

Sample outputs from two different algorithms are shown in Figure 5.

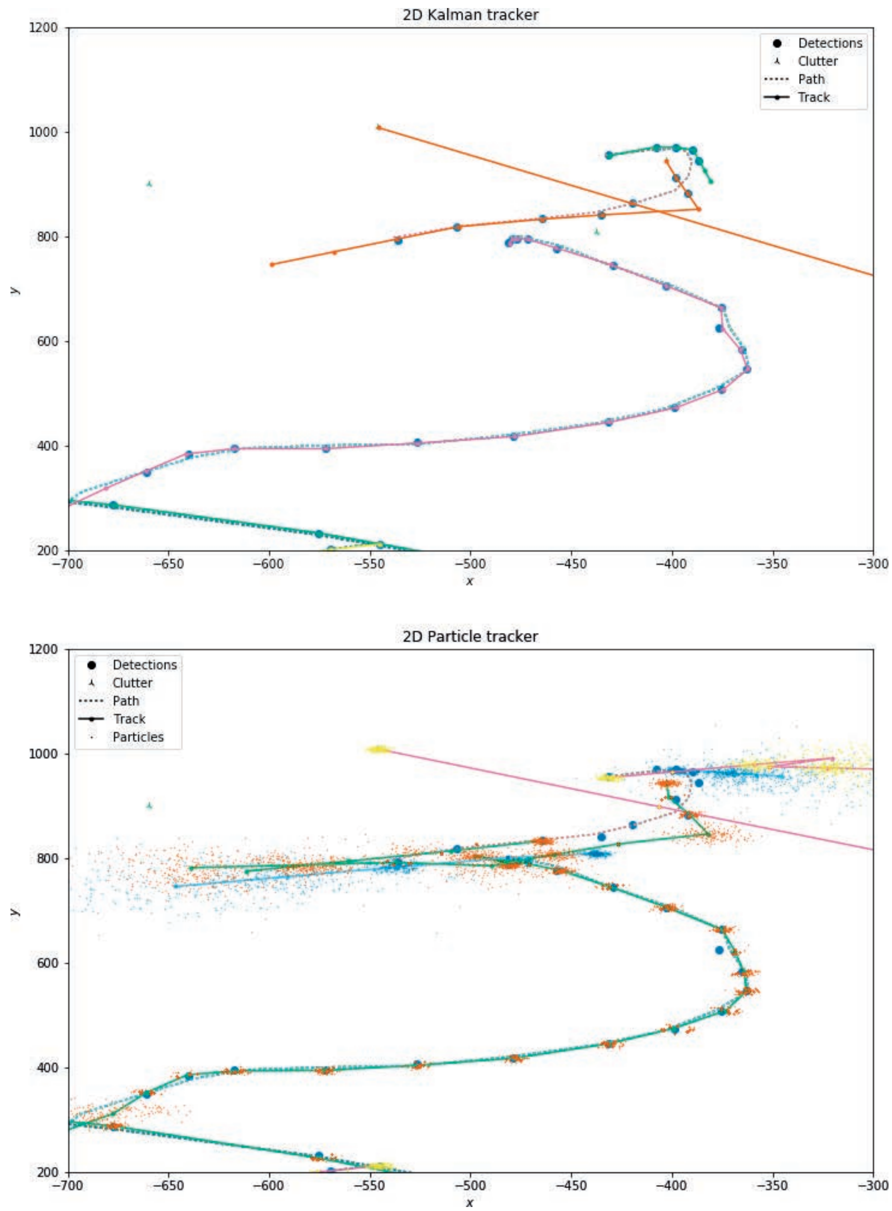

Figure 5
Output from the alpha version of Stone Soup, showing swap of Kalman filter (KF; above) with particle filter (PF; below) component against the same data with all other components the same. Note the differences in behavior during the target's execution of the tight turn at the top right and also the slow turn at the center right. Note: These plots were produced with simplistic implementations of both filters to test algorithm exchange and the interfaces only. No general conclusions of KF or PF performance should be taken from these plots.

THE STONE SOUP STORY

Stone soup is an old European folklore story, with many versions told in several countries. Here is the authors' version, capturing the essence of all the versions but not corresponding exactly with any particular one.

A traveler arrives in a village seeking food and shelter. Upon arrival, he discovers all the inns and shops are closed, and there is no food at the market. The villagers tell him there is no food in this village, and he should move on. Undeterred, the traveler produces a large pot from his backpack and proceeds to fill it with water from the stream. He then drops several large stones in it and places the pot over a fire in the market square. The villagers become curious and gather round, asking what he is doing. The traveler announces that stone soup is being made and that it is very nutritious, although it needs some time to develop its full potential.

By this time, most of the village has gathered round, thinking our traveler to be mad. He is playing the crowd, "Nothing better than stone soup," he says, "except perhaps stone soup with herbs." One of the villagers does not mind parting with a few stalks of thyme from the garden. "Could do with a little bit of body," says the traveler, and another villager finds some old potatoes from the larder. "Still needs a little bit of garnish to improve the flavor," he says, and an old cabbage and some salt beef is found by the villagers. Eventually, more and more villagers make contributions and a delicious soup is produced. Finally, the traveler removes stones from the pot, and the nourishing soup is shared around the village.

Moral: By working together, with everyone contributing what they can, a greater good is achieved.

Of course, in the case of the original story, the soup is consumed. However, in the case of a software project, the output from the collaboration will remain to benefit everyone into the future.

INTERFACE STRUCTURE

The fundamental requirement of Stone Soup is to enable the comparison of different algorithmic approaches against the same data or simulated scenario. Thus, algorithms must be interchangeable at the state and measurement model level.

Therefore, the key to the success of the framework is the creation of an underlying interface structure that enables algorithm interchangeability across all supported algorithm classes and can cope with all supported data types. This is more complex than it seems because, for example, the algorithms represent uncertainty in different ways, e.g., algorithms based around the Kalman filter model a target state distribution as a mixture of one or more Gaussian distributions, whereas particle filters represent the distribution by a set of weighted samples.

Furthermore, the framework must support application of a measurement model to data from a variety of sensors. In effect, this enforces "data interchangeability." Examples of sensor models will include range and bearing, bearings only, range only, categorical (identity) data, or a combination of them, among many others.

"The Stone Soup development team is working toward a beta release of the software in April 2019 on a public repository of GitHub."

METRICS

Assessment of candidate tracking and state estimation algorithms requires a means of objective evaluation by using a set of metrics corresponding to characteristics of interest to operational systems [6]. In certain circumstances, knowledge of the actual number of entities and their states may be available, such as in simulations. In other circumstances, e.g., when real data has been collected, full knowledge of the number of entities and their states may not be available.

Priority for the initial phases of Stone Soup will be to enable assessments in the presence of entity "truth" information. In this case, an absolute evaluation of each alternative algorithm can be conducted by comparing the tracking and state estimation output against the truth data. Typically, a data association approach is first used to associate track data with entity truth data [6]. Subsequently, performance metrics can be applied to quantify tracking characteristics. As with other aspects of Stone Soup, the intention is to develop further performance metrics as the project progresses.

JOINING IN

The Stone Soup project will be the core of a new Working Group of ISIF,[7] namely, the Open Source Tracking and Estimation Working Group (OSTEWG). This was approved at the ISIF Board of Directors meeting that coincided with FUSION 2018. OSTEWG will enable a wider outreach with the firm aspiration of building Stone Soup into the heart of the fusion community, centered around meetings at each annual FUSION conference. OSTEWG's charter is currently in development, and the first meeting will be aligned with FUSION 2019 in Ottawa, Canada. This will be timely, as it will occur shortly after Stone Soup's beta release.

The intention is for OSTEWG to set challenges supported by data within the Stone Soup framework each year at the fusion conferences. This is a popular model (exemplified by

[7] http://isif.org/working-groups/isif-working-groups.

computer vision competitions at CVPR,[8] data science competitions hosted through Kaggle[9]) that encourages participation across the community. The intention is that data would be publicly accessible (although each data set will likely have caveats), and challenge entrants would provide their solution in a Stone Soup–compatible format for evaluation at the following FUSION conference. Innovative approaches could also become papers at a special session each year.

We predict that the tracking and state estimation community will derive significant benefits from this work, including access to a repository of tracking and state estimation algorithms, framework for evaluation of multiple algorithms, and access to challenging data sets. Membership of the Working Group of ISIF is growing, as this initiative becomes known, and much interest was generated at the recent FUSION 2018 conference. Membership is still open, and any interested party should contact the corresponding author.

ACKNOWLEDGMENTS

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[8] http://cvpr2018.thecvf.com/.
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State and Trajectory Estimation Using Accumulated State Densities

Abstract—In tracking and sensor data fusion applications, the full information on kinematic object properties accumulated over a certain discrete time window up to the present time is contained in the conditional joint probability density function of the kinematic state vectors referring to each time step in this window. This density is conditioned by the time series of all sensor data collected at the present time and has accordingly been called an accumulated state density (ASD). ASDs provide a unified treatment of filtering and retrodiction insofar as by marginalizing them appropriately, the standard filtering and retrodiction densities are obtained. In addition, ASDs fully describe the posterior correlations between the states at different instants of time. Therefore, the closed-form solution of ASDs are directly connected to many real-world problems. This article presents an overview of the applications such as out-of-sequence processing, smoothing, distributed filtering, and batch processing.

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ON THE PROBLEM OF TRACKING OBJECTS

To a degree never known before, decision makers in a net-centric world have access to vast amounts of data. For effective use of this information potential in real-world applications, however, the data streams must not overwhelm the decision makers involved. On the contrary, the data must be fused in such a way that high-quality information for situation pictures results, the basis for decision making.

Situation pictures are produced by spatiotemporally processing various pieces of sensor information that in themselves often have only limited value for understanding the underlying situation. In this context, object "tracks" are of particular importance [1], [2], [3]. Tracking faces an omnipresent aspect in real-world application insofar as it is dealing with fusion of data produced at different instants of time; i.e., tracking is important in all applications in which a particular emphasis is placed on sensor data given by time series.

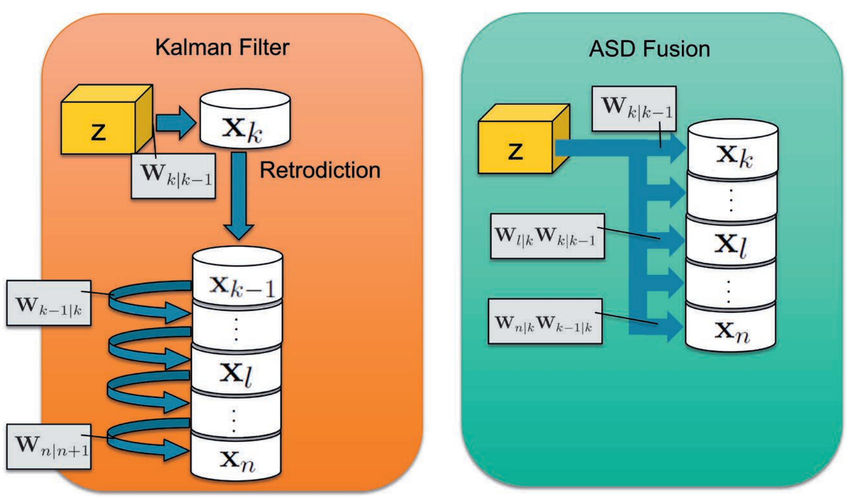

Figure 1
Schematic comparison of ASD and Kalman filter fusion.

In most tracking algorithms, the characteristics of conditional probability densities $p(\mathbf{x}_l \mid Z^k)$ of (joint) object states $\mathbf{x}_l$ are calculated, which describe the available knowledge of the object properties at a certain instant of time t_l, given a time series Z^k of imperfect sensor data accumulated up to time t_k. In certain applications, however, the kinematic object states $\mathbf{x}_k,\ldots,\mathbf{x}_n$, $n \leq k$,[1] accumulated over a certain time window from a past instant of time t_n up to the present time t_k is of interest. The statistical properties of the accumulated state vectors are completely described by the joint probability density function (pdf) of them, $p(\mathbf{x}_k,\ldots,\mathbf{x}_n \mid Z^k)$, which is conditioned by the time series Z^k. These densities may be called accumulated state densities (ASDs) [4]. By marginalizing them, the standard filtering and retrodiction densities directly result; in other words, ASDs provide a unified description of filtering and retrodiction as shown schematically

[1] Note that in the notation used here, the newest state $\mathbf{x}_k$ comes first, then older states in time-reversed order.

in Figure 1. In addition, ASDs fully describe the correlations between the state estimates at different instants of time.

In [5], for example, ASDs are considered to provide a more comprehensive treatment of issues in particle filtering. To some extent, the notion of ASDs might be considered as a step backward insofar as in the old days of object tracking it was known that one could express a linear-Gaussian estimation problem in a joint, i.e., "accumulated" fashion, while Kalman's approach was a way to find a recursive solution. Nevertheless, as shown in this article, it is useful for various tracking applications to have a *recursive* algorithm to find the parameters of an ASD.

In this article, the closed-form solution for the ASD posterior density is provided together with a couple of algorithms for various applications. The applications discussed in this article are processing of out-of-sequence (OoS) measurements, smoothing, batch processing of measurements, and distributed estimation.

This article is organized as follows. The Bayesian Tracking Paradigm section summarizes basic facts of the Bayesian tracking paradigm. In the Notion of ASD section, the ASD is introduced along with a discussion of closed formulae for the parameters of the ASD in the case in which Kalman filtering can be applied to tracking. The use of ASDs for solving the various applications, such as OoS processing, smoothing, batch processing, and distributed tracking, are the topic of Selected Applications of ASDs section. Algorithms are provided within each section.

THE BAYESIAN TRACKING PARADIGM

A Bayesian tracking algorithm is an iterative updating scheme for calculating conditional pdfs $p(\mathbf{x}_l \mid Z^k)$ that represent all available knowledge on the object states $\mathbf{x}_l$ at discrete instants of time t_l. The densities are explicitly conditioned by the sensor data Z^k accumulated up to some time t_k, typically the present time. Implicitly, they are also determined by all available context knowledge on the sensor characteristics, the dynamical object properties, the environment of the objects, topographical maps, or tactical rules governing the objects' overall behavior.

With respect on the instant of time t_l at which estimates of the object states $\mathbf{x}_l$ are required, the related density iteration process is referred to as *prediction* ($t_l > t_k$), *filtering* ($t_l = t_k$), or *retrodiction* ($t_l < t_k$). The propagation of the probability densities involved is given by three basic update equations.

PREDICTION

The prediction density $p(\mathbf{x}_k \mid Z^{k-1})$ is obtained by combining the evolution model $p(\mathbf{x}_k \mid \mathbf{x}_{k-1})$ with the previous filtering density $p(\mathbf{x}_{k-1} \mid Z^{k-1})$:

$$p\left(\mathbf{x}_{k-1} \mid Z^{k-1}\right) \xrightarrow[\text{constraints}]{\text{evolution model}} p\left(\mathbf{x}_k \mid Z^{k-1}\right) \tag{1}$$

$$p\left(\mathbf{x}_k \mid Z^{k-1}\right) = \int \mathrm{d}\mathbf{x}_{k-1}\ \underbrace{p\left(\mathbf{x}_k \mid \mathbf{x}_{k-1}\right)}_{\text{evolution model}} \underbrace{p\left(\mathbf{x}_{k-1} \mid Z^{k-1}\right)}_{\text{previous filtering}}.$$

FILTERING

The filtering density $p(\mathbf{x}_k \mid Z^k)$ is obtained by combining the sensor model $p(Z_k \mid \mathbf{x}_k)$, also called the "likelihood function," with the prediction density $p(\mathbf{x}_k \mid Z^{k-1})$ according to

$$p\left(\mathbf{x}_k \mid Z^{k-1}\right) \xrightarrow[\text{sensor model}]{\text{current sensor data}} p\left(\mathbf{x}_k \mid Z^k\right) \tag{2}$$

$$p\left(\mathbf{x}_k \mid Z^k\right) = \frac{p\left(Z_k \mid \mathbf{x}_k\right) p\left(\mathbf{x}_k \mid Z^{k-1}\right)}{\int \mathrm{d}\mathbf{x}_k\ \underbrace{p\left(Z_k \mid \mathbf{x}_k\right)}_{\text{sensor model}} \underbrace{p\left(\mathbf{x}_k \mid Z^{k-1}\right)}_{\text{prediction}}}.$$

RETRODICTION

The retrodiction density $p(\mathbf{x}_l \mid Z^k)$ is obtained by combining the object evolution model $p(\mathbf{x}_{l+1} \mid \mathbf{x}_l)$ with the previous prediction and filtering densities according to:

$$p\left(\mathbf{x}_l \mid Z^k\right) \xleftarrow[\text{evolution model}]{\text{filtering, prediction}} p\left(\mathbf{x}_{l+1} \mid Z^k\right) \tag{3}$$

$$p\left(\mathbf{x}_l \mid Z^k\right) = \int \mathrm{d}\mathbf{x}_{l+1} \frac{\overbrace{p\left(\mathbf{x}_{l+1} \mid \mathbf{x}_l\right)}^{\text{evolution}} \overbrace{p\left(\mathbf{x}_l \mid Z^l\right)}^{\text{prev. filtering}}}{\underbrace{p\left(\mathbf{x}_{l+1} \mid Z^l\right)}_{\text{prev. prediction}}} \underbrace{p\left(\mathbf{x}_{l+1} \mid Z^k\right)}_{\text{prev. retrodiction}}.$$

Being the natural antonym of prediction, the technical term retrodiction was introduced by Oliver Drummond in a series of papers [6]. Adopting the standard terminology [7], we could speak of *fixed-interval* retrodiction.

According to this paradigm, an *object track* represents all relevant knowledge on a time varying object state of interest, including its history and measures that describe the quality of this knowledge. As a technical term, "track" is therefore either a synonym for the collection of densities $p(\mathbf{x}_l \mid Z^k)$, $l = 1, \ldots, k, \ldots$, or of suitably chosen parameters characterizing them, such as estimates related to appropriate risk functions and the corresponding estimation error covariance matrices.

NOTION OF ASD

All information on the object states accumulated over a time window $t_k, t_{k-1}, \ldots, t_n$ of length $k - n + 1$,

$$\mathbf{x}_{k:n} = \left(\mathbf{x}_k^\top, \ldots, \mathbf{x}_n^\top\right)^\top \tag{4}$$

that can be extracted from the time series of accumulated sensor data Z^k up to and including time t_k is contained in a joint density function $p(\mathbf{x}_{k:n} \mid Z^k)$, which may be called ASD. Here, t_k typically denotes the current time, and $t_n \leq t_k$ is the time of initialization or the lower bound of a sliding time window. Via marginalizing over $\mathbf{x}_k, \ldots, \mathbf{x}_{l+1}, \mathbf{x}_{l-1}, \ldots, \mathbf{x}_n$,

$$p\left(\mathbf{x}_l \mid Z^k\right) = \int \mathrm{d}\mathbf{x}_k, \ldots, \mathrm{d}\mathbf{x}_{l+1}, \mathrm{d}\mathbf{x}_{l-1}, \ldots, \mathrm{d}\mathbf{x}_n \; p\left(\mathbf{x}_k, \ldots, \mathbf{x}_n \mid Z^k\right), \tag{5}$$

the filtering density $p(\mathbf{x}_k \mid Z^k)$ for $l = k$ and the retrodiction densities $p(\mathbf{x}_l \mid Z^k)$ for $l < k$ result from the ASD. ASDs, thus, in a way unify the notions of filtering and retrodiction. In addition, ASDs also contain all mutual correlations between the individual object states at different instants of time. Bayes' theorem provides a recursion formula for updating ASDs:

$$p\left(\mathbf{x}_{k:n} \mid Z^k\right) = \frac{p\left(Z_k \mid \mathbf{x}_k\right) p\left(\mathbf{x}_k \mid \mathbf{x}_{k-1}\right) p\left(\mathbf{x}_{k-1:n} \mid Z^{k-1}\right)}{\int \mathrm{d}\mathbf{x}_{k:n} \; p\left(Z_k \mid \mathbf{x}_k\right) p\left(\mathbf{x}_k \mid \mathbf{x}_{k-1}\right) p\left(\mathbf{x}_{k-1:n} \mid Z^{k-1}\right)}. \tag{6}$$

The sensor data Z_k from time t_k explicitly appears in this representation. A little formalistically speaking, “sensor data processing” means nothing else than to achieve by certain reformulations that the sensor data is no longer explicitly present.

Under conditions in which Kalman filtering is applicable (perfect data sensor-data-to-track association, linear Gaussian sensor, and evolution models), a closed-form representation of $p(\mathbf{x}_{k:n} \mid Z^k)$ can be derived. In this case, let the likelihood function be given by

$$p\left(Z_k \mid \mathbf{x}_k\right) = \mathcal{N}\left(z_k; \mathbf{H}_k \mathbf{x}_k, \mathbf{R}_k\right), \tag{7}$$

where $Z_k = \mathbf{z}_k$ denotes the vector of sensor measurements at time t_k, $\mathbf{x}_k = \mathbf{x}_k$ the kinematic state vector of the object, $\mathbf{H}_k$ the measurement matrix, and $\mathbf{R}_k$ the measurement error covariance matrix, while the Markovian evolution model of the object is represented by

$$p\left(\mathbf{x}_k \mid \mathbf{x}_{k-1}\right) = \mathcal{N}\left(\mathbf{x}_k; \mathbf{F}_{k|k-1} \mathbf{x}_{k-1}, \mathbf{Q}_{k|k-1}\right) \tag{8}$$

with an evolution matrix $\mathbf{F}_{k|k-1}$ and a corresponding evolution covariance matrix $\mathbf{Q}_{k|k-1}$. For given initial knowledge $p\left(\mathbf{x}_n \mid Z^n\right) = \mathcal{N}\left(\mathbf{x}_n; \mathbf{x}_{n|n}, \mathbf{P}_{n|n}\right)$ and for $k = 1, 2, \ldots$, the filtered parameters are the result of the well-known prediction-filtering recursion given by

$$p\left(\mathbf{x}_{k+1} \mid Z^k\right) = \mathcal{N}\left(\mathbf{x}_{k+1}; \mathbf{x}_{k+1|k}, \mathbf{P}_{k+1|k}\right) \tag{9}$$

$$\mathbf{x}_{k+1|k} = \mathbf{F}_{k+1|k} \mathbf{x}_{k|k} \tag{10}$$

$$\mathbf{P}_{k+1|k} = \mathbf{F}_{k+1|k} \mathbf{P}_{k|k} \mathbf{F}_{k+1|k}^\top + \mathbf{Q}_{k+1|k}, \tag{11}$$

and

$$p\left(\mathbf{x}_k \mid Z^k\right) = \mathcal{N}\left(\mathbf{x}_k; \mathbf{x}_{k|k}, \mathbf{P}_{k|k}\right) \tag{12}$$

$$\mathbf{x}_{k|k} = \begin{cases} \mathbf{x}_{k|k-1} + \mathbf{W}_{k|k-1}\left(\mathbf{z}_k - \mathbf{H}_k \mathbf{x}_{k|k-1}\right) \\ \mathbf{P}_{k|k}\left(\mathbf{P}_{k|k-1}^{-1} \mathbf{x}_{k|k-1} + \mathbf{H}_k^\top \mathbf{R}_k^{-1} \mathbf{z}_k\right) \end{cases} \tag{13}$$

$$\mathbf{P}_{k|k} = \begin{cases} \mathbf{P}_{k|k-1} - \mathbf{W}_{k|k-1} \mathbf{S}_{k|k-1} \mathbf{W}_{k|k-1}^\top \\ \left(\mathbf{P}_{k|k-1}^{-1} + \mathbf{H}_k^\top \mathbf{R}_k^{-1} \mathbf{H}_k\right)^{-1}. \end{cases} \tag{14}$$

There exist two equivalent formulations of the Kalman update formulae according to the two versions of the product formula (74). The innovation covariance matrix $\mathbf{S}_{l|l-1}$ and the *Kalman gain* matrix at some given time t_l are given by

$$\mathbf{S}_{l|l-1} = \mathbf{H}_l \mathbf{P}_{l|l-1} \mathbf{H}_l^\top + \mathbf{R}_l. \tag{15}$$

$$\mathbf{W}_{l|l-1} = \mathbf{P}_{l|l-1} \mathbf{H}_l^\top \mathbf{S}_{l|l-1}^{-1}. \tag{16}$$

Because ASD states $\mathbf{x}_k, \ldots \mathbf{x}_n$ are conditioned on the full data Z^k up to time t_k, its mean and covariance is directly related to the result of the well-known Rauch–Tung–Striebel (RTS) recursion

$$\mathbf{x}_{l|k} = \mathbf{x}_{l|l} + \mathbf{W}_{l|l+1}\left(\mathbf{x}_{l+1|k} - \mathbf{x}_{l+1|l}\right) \tag{17}$$

$$\mathbf{P}_{l|k} = \mathbf{P}_{l|l} + \mathbf{W}_{l|l+1}\left(\mathbf{P}_{l+1|k} - \mathbf{P}_{l+1|l}\right) \mathbf{W}_{l|l+1}^\top, \tag{18}$$

and a “retrodiction gain” matrix

$$\mathbf{W}_{l|l+1} = \mathbf{P}_{l|l} \mathbf{F}_{l+1|l}^\top \mathbf{P}_{l+1|l}^{-1}. \tag{19}$$

Now, using the abbreviation

$$\mathbf{D}_{l|k} = \mathbf{P}_{l|k} - \mathbf{W}_{l|l+1} \mathbf{P}_{l+1|k} \mathbf{W}_{l|l+1}^\top. \tag{20}$$

the closed-form solution of the ASD posterior in the linear-Gaussian case is given by the multivariate normal distribution

$$p\left(\mathbf{x}_{k:n} \mid Z^k\right) = \mathcal{N}\left(\mathbf{x}_{k:n}; \mathbf{x}_{k:n|k}, \mathbf{P}_{k:n|k}\right), \tag{21}$$

with a joint expectation vector $\mathbf{x}_{k:n|k}$ defined by

$$\mathbf{x}_{k:n|k} = \left(\mathbf{x}_{k|k}^\top, \mathbf{x}_{k-1|k}^\top, \ldots, \mathbf{x}_{n|k}^\top\right)^\top, \tag{22}$$

while the corresponding joint covariance matrix $\mathbf{P}_{k:n|k}$ can be written as an inverse of a tridiagonal block matrix that is given in (23). The tridiagonal structure is a consequence of the Markov property of the underlying evolution model. This representation of the inverse of $\mathbf{P}_{k:n|k}$ is useful in practical calculations.

By a repeated use of the matrix inversion lemma (see the Appendix) and an induction argument, the inverse of this tridiagonal block matrix can be calculated. The resulting block matrix is given in (24). For this representation, the following abbreviations were used:

$$
\mathbf{P}^{-1}_{k:n|k} = \begin{pmatrix} \mathbf{T}_{k|k} & -\mathbf{W}^{\top}_{k-1|k}\mathbf{D}^{-1}_{k-1|k} & \mathbf{O} & \cdots & \mathbf{O} \\ -\mathbf{D}^{-1}_{k-1|k}\mathbf{W}_{k-1|k} & \mathbf{T}_{k-1|k} & -\mathbf{W}^{\top}_{k-2|k}\mathbf{Q}^{-1}_{k-2|k} & \ddots & \vdots \\ \mathbf{O} & -\mathbf{D}^{-1}_{k-2|k}\mathbf{W}_{k-2|k} & \ddots & \ddots & \mathbf{O} \\ \vdots & \ddots & \ddots & \mathbf{T}_{n+1|k} & -\mathbf{W}^{\top}_{n|k}\mathbf{D}_{n|k} \\ \mathbf{O} & \cdots & \mathbf{O} & -\mathbf{D}_{n|k}\mathbf{W}_{n|k} & \mathbf{T}_{n|k} \end{pmatrix}. \tag{23}
$$

$$
\mathbf{P}_{k:n|k} = \begin{pmatrix} \mathbf{P}_{k|k} & \mathbf{P}_{k|k}\mathbf{W}^{\top}_{k-1|k} & \mathbf{P}_{k|k}\mathbf{W}^{\top}_{k-2|k} & \cdots & \mathbf{P}_{k|k}\mathbf{W}^{\top}_{n|k} \\ \mathbf{W}_{k-1|k}\mathbf{P}_{k|k} & \mathbf{P}_{k-1|k} & \mathbf{P}_{k-1|k}\mathbf{W}^{\top}_{k-2|k-1} & * & \mathbf{P}_{k-1|k}\mathbf{W}^{\top}_{n|k-1} \\ \mathbf{W}_{k-2|k}\mathbf{P}_{k|k} & \mathbf{W}_{k-2|k-1}\mathbf{P}_{k-1|k} & \mathbf{P}_{k-2|k} & * & \vdots \\ \vdots & * & * & * & \mathbf{P}_{n+1|k}\mathbf{W}^{\top}_{n|n+1} \\ \mathbf{W}_{n|k}\mathbf{P}_{k|k} & \mathbf{W}_{n|k-1}\mathbf{P}_{k-1|k} & \cdots & \mathbf{W}_{n|n+1}\mathbf{P}_{n+1|k} & \mathbf{P}_{n|k} \end{pmatrix}, \tag{24}
$$

$$
\mathbf{W}_{l|k} = \prod_{\lambda=l}^{k-1}\mathbf{W}_{\lambda|\lambda+1} = \prod_{\lambda=l}^{k-1}\mathbf{P}_{\lambda|\lambda}\mathbf{F}^{\top}_{\lambda+1|\lambda}\mathbf{P}^{-1}_{\lambda+1|\lambda}. \tag{25}
$$

The densities $\left\{\mathcal{N}\left(\mathbf{x}_l;\mathbf{x}_{l|k},\mathbf{P}_{l|k}\right)\right\}_{l=n}^{k}$ are directly obtained via marginalizing, because the covariance matrices $\mathbf{P}_{l|k}$, $n \le l \le k$, appear on the diagonal of this block matrix. Note that the ASD is completely defined by the results of prediction, filtering, and retrodiction obtained for the time window $t_k, \ldots, t_n$, i.e., it is a by-product for Kalman filtering and RTS smoothing. It is not surprising that the smoothed estimates and the error covariances appear as the block entries in the mean and the block covariance, respectively. However, the interesting result is to have a closed-form solution for the structure of the joint covariance matrix. In particular, the cross covariances of states at different instants of time can be taken from the off-diagonal entries of $\mathbf{P}_{k:n|k}$.

RECURSIVE ASD FILTER IMPLEMENTATION

The following sections show how to iteratively calculate the parameters $\mathbf{x}_{k:n|k}$ and $\mathbf{P}_{k:n|k}$. A short summary for a straightforward implementation is provided in Table 1. Assume the posterior ASD at time t_{k-1} is given in terms of $\mathbf{x}_{k-1:n|k-1}$ and $\mathbf{P}_{k-1:n|k-1}$. The prediction of the state is straightforward due to the Markov proposition:

$$
\mathbf{x}_{k:n|k-1} = \left(\mathbf{x}^{\top}_{k|k-1} \quad \mathbf{x}^{\top}_{k-1|k-1} \quad \cdots \quad \mathbf{x}^{\top}_{n|k-1}\right)^{\top}, \tag{26}
$$

where $\mathbf{x}_{k|k-1} = \mathbf{F}_{k|k-1}\mathbf{x}_{k-1|k-1}$ is equivalent to a Kalman filter prediction. For the ASD covariance prediction, a recursive formulation of the ASD covariance in (24) is used:

$$
\mathbf{P}_{k:n|k-1} = \begin{pmatrix} \mathbf{P}_{k|k-1} & \mathbf{P}_{k|k-1}\mathbf{W}^{\top}_{k-1:n} \\ \mathbf{W}_{k-1:n}\mathbf{P}_{k|k-1} & \mathbf{P}_{k-1:n|k-1} \end{pmatrix}, \tag{27}
$$

where

$$
\mathbf{P}_{k|k-1} = \mathbf{F}_{k|k-1}\mathbf{P}_{k-1|k-1}\mathbf{F}^{\top}_{k|k-1} + \mathbf{Q}_{k|k-1}, \tag{28}
$$

$$
\mathbf{W}_{k-1:n} = \begin{pmatrix} \mathbf{W}_{k-1|k} \\ \mathbf{W}_{k-2:n}\mathbf{W}_{k-1|k} \end{pmatrix}. \tag{29}
$$

Table 1

Recursive ASD Algorithm

Initialization	Set $\mathbf{x}_{0\|0}, \mathbf{P}_{0\|0}$.
Prediction $t_0 \to t_1$	$\mathbf{x}_{1\|0} = \mathbf{F}_{1\|0}\mathbf{x}_{0\|0}$ $\mathbf{P}_{1\|0} = \mathbf{F}_{1\|0}\mathbf{P}_{0\|0}\mathbf{F}^{\top}_{1\|0} + \mathbf{Q}_{1\|0}$ $\mathbf{x}_{1:0\|0} = \left(\mathbf{x}^{\top}_{1\|0}\mathbf{x}^{\top}_{0\|0}\right)^{\top}$ $\mathbf{P}_{1:0\|0} = \begin{pmatrix} \mathbf{P}_{1\|0} & \mathbf{F}_{1\|0}\mathbf{P}_{0\|0} \\ \mathbf{P}_{0\|0}\mathbf{F}^{\top}_{1\|0} & \mathbf{P}_{0\|0} \end{pmatrix}$
Filtering $\mathbf{z}_1$ at t_1	$\Pi_1 = (\mathbf{I}, \mathbf{O})$ $\mathbf{S}_1 = \mathbf{H}_1\Pi_1\mathbf{P}_{1:0\|0}\Pi^{\top}_1\mathbf{H}^{\top}_1 + \mathbf{R}_1$ $\mathbf{W}_{1:0\|0} = \mathbf{P}_{1:0\|0}\Pi^{\top}_1\mathbf{H}^{\top}_1\mathbf{S}^{-1}_1$ $\mathbf{x}_{1:0\|1} = \mathbf{x}_{1:0\|0} + \mathbf{W}_{1:0\|0}\left(\mathbf{z}_1 - \mathbf{H}_1\Pi_1\mathbf{x}_{1:0\|0}\right)$ $\mathbf{P}_{1:0\|1} = \mathbf{P}_{1:0\|0} - \mathbf{W}_{1:0\|0}\mathbf{S}_1\mathbf{W}^{\top}_{1:0\|0}$
Prediction $t_{k-1} \to t_k$	$\mathbf{x}_{k\|k-1} = \mathbf{F}_{k\|k-1}\mathbf{x}_{k-1\|k-1}$ $\mathbf{P}_{k\|k-1} = \mathbf{F}_{k\|k-1}\mathbf{P}_{k-1\|k-1}\mathbf{F}^{\top}_{k\|k-1} + \mathbf{Q}_{k\|k-1}$ $\mathbf{x}_{k:0\|k-1} = \left(\mathbf{x}^{\top}_{k\|k-1}\mathbf{x}^{\top}_{k-1:0\|k-1}\right)^{\top}$ $\mathbf{P}^{(k-1)}_{k-1:n\|k-1} = \begin{pmatrix} \mathbf{P}_{k-1\|k-1} \\ \mathbf{W}_{k-2\|k-1}\mathbf{P}_{k-1\|k-1} \\ \vdots \\ \mathbf{W}_{0\|k-1}\mathbf{P}_{k-1\|k-1} \end{pmatrix}$ $\mathbf{P}_{k:n\|k-1} = \begin{pmatrix} \mathbf{P}_{k\|k-1} & \mathbf{F}_{k\|k-1}\left(\mathbf{P}^{(k-1)}_{k-1:n\|k-1}\right)^{\top} \\ \mathbf{P}^{(k-1)}_{k-1:n\|k-1}\mathbf{F}^{\top}_{k\|k-1} & \mathbf{P}_{k-1:n\|k-1} \end{pmatrix}$
Filtering $\mathbf{z}_k$ at t_k	$\Pi_k = (\mathbf{I}, \mathbf{O}, \ldots, \mathbf{O})$ $\mathbf{S}_k = \mathbf{H}_k\Pi_k\mathbf{P}_{k:0\|k-1}\Pi^{\top}_k\mathbf{H}^{\top}_k + \mathbf{R}_k$ $\mathbf{W}_{k:0\|k-1} = \mathbf{P}_{k:0\|k-1}\Pi^{\top}_k\mathbf{H}^{\top}_k\mathbf{S}^{-1}_k$ $\mathbf{x}_{k:0\|k} = \mathbf{x}_{k:0\|k-1} + \mathbf{W}_{k:0\|k-1}\left(\mathbf{z}_k - \mathbf{H}_k\Pi_k\mathbf{x}_{k:0\|k-1}\right)$ $\mathbf{P}_{k:0\|k} = \mathbf{P}_{k:0\|k-1} - \mathbf{W}_{k:0\|k-1}\mathbf{S}_k\mathbf{W}^{\top}_{k:0\|k-1}$
Sliding Window	Prune estimate for t_n from $\mathbf{x}_{k:n\|n}$.
	Prune column and row for t_n from $\mathbf{P}_{k:n\|n}$.

The expression in (27) can be simplified to

$$
\mathbf{P}_{k:n|k-1} = \begin{pmatrix} \mathbf{P}_{k|k-1} & \mathbf{F}_{k|k-1}\left(\mathbf{P}^{(k-1)}_{k-1:n|k-1}\right)^{\top} \\ \mathbf{P}^{(k-1)}_{k-1:n|k-1}\mathbf{F}^{\top}_{k|k-1} & \mathbf{P}_{k-1:n|k-1} \end{pmatrix}, \tag{30}
$$

where $\mathbf{P}^{(k-1)}_{k-1:n|k-1}$ represents the $(k-1)$th block column for $n = 1$.

For the filtering step, it is assumed that the prior parameters $\mathbf{x}_{k:n|k-1}$ and $\mathbf{P}_{k:n|k-1}$ are given. As the measurement error is assumed to be independent from the past, the sensor likelihood function can be expressed by an application of projections Π_k onto the current state:

$$
p\left(\mathbf{z}_k \mid \mathbf{x}_k\right) = p\left(\mathbf{z}_k \mid \Pi_k\mathbf{x}_{k:n}\right) \tag{31}
$$

$$= \mathcal{N}\left(\mathbf{z}_k; \mathbf{H}_k \Pi_k \mathbf{x}_{k:n}, \mathbf{R}_k\right), \tag{32}$$

where

$$\Pi_k = \left(\mathbf{I}, \mathbf{O}, \ldots, \mathbf{O}\right). \tag{33}$$

In the previous notation, $\mathbf{I}$ is an identity matrix in the dimension of the state, and $\mathbf{O}$ is the corresponding zero matrix. Then, the posterior parameters are obtained by the multiplication of the local prior density and the likelihood function. An application of the product formula in the Appendix yields

$$\mathbf{x}_{k:n|k} = \mathbf{x}_{k:n|k-1} + \mathbf{W}_{k:n|k-1}\left(\mathbf{z}_k - \mathbf{H}_k \Pi_k \mathbf{x}_{k:n|k-1}\right), \tag{34}$$

$$\mathbf{P}_{k:n|k} = \mathbf{P}_{k:n|k-1} - \mathbf{W}_{k:n|k-1} \mathbf{S}_k \mathbf{W}_{k:n|k-1}^\top \tag{35}$$

$$\mathbf{W}_{k:n|k-1} = \mathbf{P}_{k:n|k-1} \Pi_k^\top \mathbf{H}_k^\top \mathbf{S}_k^{-1}, \tag{36}$$

$$\mathbf{S}_k = \mathbf{H}_k \Pi_k \mathbf{P}_{k:n|k-1} \Pi_k^\top \mathbf{H}_k^\top + \mathbf{R}_k. \tag{37}$$

Note that the dimension of $\mathbf{S}_k$ is in the dimension of $\mathbf{z}_k$, which is small in most applications. Moreover, as stated previously, the smoothed states and covariances, respectively, are obtained by a single update step.

SELECTED APPLICATIONS OF ASDS

SMOOTHING

If the estimation of the trajectory of all states at multiple instants of time is of interest, smoothing or retrodiction has to be applied. The updated states conditioned on the complete set of sensor data up to time t_k can be obtained by the RTS equations (17) and (18). This, however, requires a second recursion that has to be initiated after each filtering step. By using the block line version of the ASD update in (34) and (35), it can easily be seen that the smoothed state that refers to time t_l is given by the equations

$$\mathbf{x}_{l|k} = \mathbf{x}_{l|k-1} + \mathbf{W}_{l|k} \mathbf{W}_{k|k-1}\left(\mathbf{z}_k - \mathbf{H}_k \mathbf{x}_{k|k-1}\right), \tag{38}$$

$$\mathbf{P}_{l|k} = \mathbf{P}_{l|k-1} - \mathbf{W}_{l|k} \mathbf{W}_{k|k-1} \mathbf{S}_{k|k-1} \mathbf{W}_{k|k-1}^\top \mathbf{W}_{l|k}^\top. \tag{39}$$

Because $\mathbf{W}_{k|k-1}(\mathbf{z}_k - \mathbf{H}_k \mathbf{x}_{k|k-1})$ is part of the Kalman filter update and that

$$\mathbf{W}_{l|k} = \mathbf{W}_{l|l+1} \mathbf{W}_{l+1|k}, \tag{40}$$

this smoothing algorithm was shown to be significantly faster than the standard RTS retrodiction [8], [9], [10].

BATCH PROCESSING

If initial conditions are given by the pdf $p\left(\mathbf{x}_n\right) = \mathcal{N}\left(\mathbf{x}_n; \mathbf{x}_{n|0}, \mathbf{P}_{n|0}\right)$ and a set of measurements $\mathbf{z}_{k:n} = \{\mathbf{z}_k, \mathbf{z}_{k-1}, \ldots, \mathbf{z}_n\}$ is to be processed, the ASD formulae directly provide the means to estimate the trajectory $\mathbf{x}_{k:n}$ on the basis of the sensor data. This can easily be seen by an application of the Bayes' theorem:

$$p\left(\mathbf{x}_{k:n} \mid Z^k\right) = \frac{p\left(\mathbf{z}_{k:n} \mid \mathbf{x}_{k:n}\right) p\left(\mathbf{x}_{k:n}\right)}{\int \mathrm{d}\mathbf{x}_{k:n}\, p\left(\mathbf{z}_{k:n} \mid \mathbf{x}_{k:n}\right) p\left(\mathbf{x}_{k:n}\right)}, \tag{41}$$

where $p(\mathbf{x}_{k:n})$ is conditioned on the initial knowledge on $\mathbf{x}_n$. Therefore, it can be obtained by a successive application of the ASD prediction (26) and (30) on the initial pdf. This yields a Gaussian density

$$p\left(\mathbf{x}_{k:n}\right) = \mathcal{N}\left(\mathbf{x}_{k:n}; \mathbf{x}_{k:n|0}, \mathbf{P}_{k:n|0}\right) \tag{42}$$

where the mean is given by

$$\mathbf{x}_{k:n|0} = \left(\mathbf{x}_{k|0}^\top \quad \mathbf{x}_{k-1|0}^\top \quad \ldots \quad \mathbf{x}_{n|0}^\top\right)^\top \tag{43}$$

and $\mathbf{P}_{k:n|0}$ is given in (47) and the following abbreviations

$$\mathbf{x}_{l|0} = \mathbf{F}_{l|0} \mathbf{x}_{n|0} = \mathbf{F}_{l|l-1} \mathbf{x}_{l-1|0} \tag{44}$$

$$\mathbf{P}_{l|0} = \mathbf{F}_{l|0} \mathbf{P}_{n|0} \mathbf{F}_{l|0}^\top + \mathbf{Q}_{l|0} \tag{45}$$

$$= \mathbf{F}_{l|l-1} \mathbf{P}_{l-1|0} \mathbf{F}_{l|l-1}^\top + \mathbf{Q}_{l|l-1} \tag{46}$$

$$\mathbf{P}_{k:n|0} = \begin{pmatrix} \mathbf{P}_{k|0} & \mathbf{F}_{k|k-1}\mathbf{P}_{k-1|0} & \cdots & & \mathbf{F}_{k|k-1}\cdots\mathbf{F}_{n+1|n}\mathbf{P}_{n|0} \\ \mathbf{P}_{k-1|0}\mathbf{F}_{k|k-1}^\top & \ddots & & & \\ \vdots & & \mathbf{P}_{n+2|0} & \mathbf{F}_{n+2|n+1}\mathbf{P}_{n+1|0} & \mathbf{F}_{n+2|n+1}\mathbf{F}_{n+1|n}\mathbf{P}_{n|0} \\ \vdots & & \mathbf{P}_{n+1|0}\mathbf{F}_{n+2|n+1}^\top & \mathbf{P}_{n+1|0} & \mathbf{F}_{n+1|n}\mathbf{P}_{n|0} \\ \mathbf{P}_{n|0}\mathbf{F}_{n+1|n}^\top\cdots\mathbf{F}_{k|k-1}^\top & \cdots & \mathbf{P}_{n|0}\mathbf{F}_{n+1|n}^\top\mathbf{F}_{n+2|n+1}^\top & \mathbf{P}_{n|0}\mathbf{F}_{n+1|n}^\top & \mathbf{P}_{n|0} \end{pmatrix} \tag{47}$$

were used. Because the measurements are mutually conditionally independent, the likelihood of the accumulated measurement set $\mathbf{z}_{k:n}$ is given by

$$p\left(\mathbf{z}_{k:n} \mid \mathbf{x}_{k:n}\right) = \mathcal{N}\left(\mathbf{z}_{k:n}; \mathbf{H}_{k:n}\mathbf{x}_{k:n}, \mathbf{R}_{k:n}\right) \tag{48}$$

where

$$\mathbf{z}_{k:n} = \left(\mathbf{z}_k^\top \quad \ldots \quad \mathbf{z}_n^\top\right)^\top, \tag{49}$$

$$\mathbf{R}_{k:n} = \mathrm{blkdiag}\left(\mathbf{R}_k \quad \ldots \quad \mathbf{R}_n\right), \tag{50}$$

$$\mathbf{H}_{k:n} = \mathrm{blkdiag}\left(\mathbf{H}_k \quad \ldots \quad \mathbf{H}_n\right). \tag{51}$$

According to Bayes' theorem an application of the product formula directly yields the fully *filtered and smoothed* trajectory is given by the posterior ASD

$$p\left(\mathbf{x}_{k:n} \mid Z^k\right) = \mathcal{N}\left(\mathbf{x}_{k:n}; \mathbf{x}_{k:n|k}, \mathbf{P}_{k:n|k}\right), \tag{52}$$

where

$$\mathbf{x}_{k:n|k} = \mathbf{x}_{k:n|0} + \mathbf{W}_{k:n|0}\left(\mathbf{z}_{k:n} - \mathbf{H}_{k:n}\mathbf{x}_{k:n|0}\right), \quad (53)$$

$$\mathbf{P}_{k:n|k} = \mathbf{P}_{k:n|0} - \mathbf{W}_{k:n|0}\mathbf{S}_{k:n}\mathbf{W}_{k:n|0}^{\top}, \quad (54)$$

$$\mathbf{W}_{k:n|0} = \mathbf{P}_{k:n|0}\mathbf{H}_{k:n}^{\top}\mathbf{S}_{k:n}^{-1}, \quad (55)$$

$$\mathbf{S}_{k:n} = \mathbf{H}_{k:n}\mathbf{P}_{k:n|0}\mathbf{H}_{k:n}^{\top} + \mathbf{R}_{k:n}. \quad (56)$$

This algorithm is summarized in Table 2. Moreover, for each instant of time t_l, there exists a weighting matrix $\mathbf{K}_{l\leftarrow n}$ and a set of matrices $\left\{\mathbf{L}_{l\leftarrow j}\right\}_{j=n}^{k}$ such that the smoothed estimate for time t_l is given by

$$\mathbf{x}_{l|k} = \mathbf{K}_{l\leftarrow n}\mathbf{x}_{n|0} + \sum_{j=n}^{k}\mathbf{L}_{l\leftarrow j}\mathbf{z}_{j}. \quad (57)$$

This can be considered as the block line version of the ASD update in (53). The proof and all details can be found in [11].

OOS PROCESSING

In many real-world applications of sensor data fusion, one has to be aware of OoS measurements. Due to latencies in the underlying communication infrastructure, for example, such measurements arrive at a processing node in a distributed data fusion system "too late," i.e., after sensor data with a later time stamp have already been processed.

Consider a measurement $\mathbf{z}_m$ produced at time t_m with $n \leq m$, i.e., possibly before the "present" time t_k, where the time series Z^k is available and has been exploited. It is now required to compute the impact of this new but late sensor information has on the present and the past target states $\mathbf{x}_l$, $l \in \{n, \ldots, k\}$, i.e. on the accumulated target state $\mathbf{x}_{k:n}$. Let $\mathbf{z}_m$ be a measurement of the target state $\mathbf{x}_m$ at time t_m characterized by a Gaussian likelihood function, which is defined by a measurement matrix $\mathbf{H}_m$ and a corresponding measurement error covariance matrix $\mathbf{R}_m$. Furthermore, it is useful to renumber the target states $\mathbf{x}_k, \ldots, \mathbf{x}_n$ such that $\mathbf{x}_k, \ldots, \mathbf{x}_m, \ldots, \mathbf{x}_n =: \mathbf{x}_{k:m:n}$ are consistent with their time stamps $(t_l)_{l=k,\ldots,m,\ldots,n}$.

To process the measurement $\mathbf{z}_m$, the prior ASD

$$p\left(\mathbf{x}_{k:m:n} \,|\, Z^k \setminus \{\mathbf{z}_m\}\right) = \mathcal{N}\left(\mathbf{x}_{k:m:n}; \mathbf{x}_{k:m:n|k}, \mathbf{P}_{k:m:n|k}\right) \quad (58)$$

is required. The parameters of this density are given by the closed-form formulae for ASDs by using the *continuous-time retrodiction* [10] for the mean and covariance of the state at time t_m:

$$\mathbf{x}_{m|k} = \mathbf{x}_{m|m-1} + \mathbf{W}_{m+1|m}\left(\mathbf{x}_{m+1|k} - \mathbf{x}_{m+1|m-1}\right), \quad (59)$$

$$\mathbf{P}_{m|k} = \mathbf{P}_{m|m-1} + \mathbf{W}_{m+1|m}\cdot\left(\mathbf{P}_{m+1|k} - \mathbf{P}_{m+1|m-1}\right)\mathbf{W}_{m+1|m}^{\top}, \quad (60)$$

$$\mathbf{x}_{m|m-1} = \mathbf{F}_{m|m-1}\mathbf{x}_{m-1|k}, \quad (61)$$

Table 2

Batch Processing Algorithm	
Initialization	Set $\mathbf{x}_{n\|0}, \mathbf{P}_{n\|0}$, gather $\{\mathbf{z}_l\}_{l=n}^{k}$
Prior up to Time t_k	For $l = n + 1, \ldots, k$ compute
	$\mathbf{x}_{l\|0} = \mathbf{F}_{l\|l-1}\mathbf{x}_{l-1\|0}$
	$\mathbf{P}_{l\|0} = \mathbf{F}_{l\|l-1}\mathbf{P}_{l-1\|0}\mathbf{F}_{l\|l-1}^{\top} + \mathbf{Q}_{l\|l-1}$
	End for
	$\mathbf{x}_{k:n\|0} = \left(\mathbf{x}_{k\|0}^{\top} \; \mathbf{x}_{k-1\|0}^{\top} \; \ldots \; \mathbf{x}_{n\|0}^{\top}\right)^{\top}$
	$\mathbf{P}_{k:n\|0}$ as in (47).
Batch Likelihood	$\mathbf{z}_{k:n} = \left(\mathbf{z}_k^{\top} \; \ldots \; \mathbf{z}_n^{\top}\right)^{\top}$,
	$\mathbf{R}_{k:n} = \mathrm{blkdiag}\left(\mathbf{R}_k \; \ldots \; \mathbf{R}_n\right)$,
	$\mathbf{H}_{k:n} = \mathrm{blkdiag}\left(\mathbf{H}_k \; \ldots \; \mathbf{H}_n\right)$.
Processing	$\mathbf{x}_{k:n\|k} = \mathbf{x}_{k:n\|0} + \mathbf{W}_{k:n\|0}\left(\mathbf{z}_{k:n} - \mathbf{H}_{k:n}\mathbf{x}_{k:n\|0}\right)$,
	$\mathbf{P}_{k:n\|k} = \mathbf{P}_{k:n\|0} - \mathbf{W}_{k:n\|0}\mathbf{S}_{k:n}\mathbf{W}_{k:n\|0}^{\top}$,
	$\mathbf{W}_{k:n\|0} = \mathbf{P}_{k:n\|0}\mathbf{H}_{k:n}^{\top}\mathbf{S}_{k:n}^{-1}$,
	$\mathbf{S}_{k:n} = \mathbf{H}_{k:n}\mathbf{P}_{k:n\|0}\mathbf{H}_{k:n}^{\top} + \mathbf{R}_{k:n}$.

$$\mathbf{P}_{m|m-1} = \mathbf{F}_{m|m-1}\mathbf{P}_{m-1|k}\mathbf{F}_{m|m-1}^{\top} + \mathbf{Q}_{m|m-1}. \quad (62)$$

In terms of the ASD state, the measurement $\mathbf{z}_m$ now is "in sequence" and can be processed by means of the ASD update equations (34) and (35). To this end, the projection onto state $\mathbf{x}_k$ has to be replaced by a projection onto $\mathbf{x}_m$.

The block line approach for the exact OoS processing is described in [11]. In this article, it is shown that the estimate for time t_l, $l \in \{n,\ldots,k\}$ is given by

$$\mathbf{W}_{l,m|k} = \mathbf{W}_{l|m}\mathbf{P}_{\max\{l,m\}|k}\mathbf{W}_{m|l}^{\top}\mathbf{H}_m^{\top}\mathbf{S}_{m|k}^{-1}. \quad (63)$$

$$\mathbf{x}_{l|k,m} = \mathbf{x}_{l|k} + \mathbf{W}_{l,m|k}\left(\mathbf{z}_m - \mathbf{H}_m\mathbf{x}_{m|k}\right), \quad (64)$$

$$\mathbf{P}_{l|k,m} = \mathbf{P}_{l|k} - \mathbf{W}_{l,m|k}\mathbf{S}_{m|k}\mathbf{W}_{l,m|k}^{\top}. \quad (65)$$

Here, the notation is extended such that $\mathbf{W}_{l|j}$ is the identity matrix for $j \leq l$.

DISTRIBUTED ASD FUSION

Often in multisensor applications, it is required to preprocess data at each sensor node to economize on bandwidth. The preprocessed parameters are then fused to the global estimate. In the literature, there exist plenty of algorithms, many of which are derived from different approaches. To provide an entire overview of those is beyond the scope of this article; therefore, we refer the reader to [2] and [3] for examples. An exact method for the linear-Gaussian case is the distributed Kalman filter (DKF) [12] and [13], i.e., the resulting fused track is equivalent to a centralized Kalman filter processing all measurements from every sensor.

The DKF, however, requires sensor models to be known to each processing node. In [14] and [15], it is shown that ASDs can be used for exact distributed fusion without the sensor parameters being globally known. This is of particular importance for applications with nonlinear measurement functions, because the linearized measurement error becomes data dependent. This is achieved by exploiting the fact that for S sensors it holds that

$$\mathcal{N}\left(\mathbf{x}_k;\mathbf{F}_{k|k-1}\mathbf{x}_{k-1},\mathbf{Q}_{k|k-1}\right) \propto \mathcal{N}\left(\mathbf{x}_k;\mathbf{F}_{k|k-1}\mathbf{x}_{k-1},S\mathbf{Q}_{k|k-1}\right)^S. \tag{66}$$

By means of a "spread" process noise covariance matrix $S\mathbf{Q}_{k|k-1}$, one achieves a product representation of *local* ASDs:

$$p\left(\mathbf{x}_{k:n} \mid Z^k\right) \propto \prod_{s=1}^{S} \mathcal{N}\left(\mathbf{x}_{k:n};\mathbf{x}^s_{k:n|k},\mathbf{P}^s_{k:n|k}\right). \tag{67}$$

Here, the parameters $\mathbf{x}^s_{k:n|k}$ and $\mathbf{P}^s_{k:n|k}$ are obtained from the closed-form solution for ASDs by using the relaxed evolution model on the right side of (66) and local data from sensor s only [14]. As a consequence, the fusion of these local parameters becomes an almost trivial convex combination:

$$\mathbf{x}_{k:n|k} = \mathbf{P}_{k:n|k}\sum_{s=1}^{S}\left(\mathbf{P}^s_{k:n|k}\right)^{-1}\mathbf{x}^s_{k:n|k} \tag{68}$$

$$\mathbf{P}_{k:n|k} = \left(\sum_{s=1}^{S}\left(\mathbf{P}^s_{k:n|k}\right)^{-1}\right)^{-1}. \tag{69}$$

This fusion rule is exact whenever the full ASD parameters are transmitted to the fusion center. By truncating the time series of estimates, an approximation is achieved that yields close to optimal results [13]. For the implementation, the interested reader can easily follow the summary in Table 3.

ASDs can also be used to perform *multistep tracklet fusion* [13]. Because the *equivalent measurements*

$$\mathbf{Y}^s_{k:n} = \left(\mathbf{P}^s_{k:n|k}\right)^{-1} - \left(\mathbf{P}^s_{k:n|n}\right)^{-1} \tag{70}$$

$$\mathbf{y}_{k:n} = \left(\mathbf{P}^s_{k:n|k}\right)^{-1}\mathbf{x}^s_{k:n|k} - \left(\mathbf{P}^s_{k:n|n}\right)^{-1}\mathbf{x}^s_{k:n|n} \tag{71}$$

are mutually independent when conditioned on the ASD state, they can be used to update a centralized ASD track:

$$\mathbf{P}_{k:n|k} = \left(\left(\mathbf{P}_{k:n|n}\right)^{-1} + \sum_{s=1}^{S}\mathbf{Y}^s_{k:n}\right)^{-1}, \tag{72}$$

$$\mathbf{x}_{k:n|k} = \mathbf{P}_{k:n|k}\left(\left(\mathbf{P}_{k:n|n}\right)^{-1}\mathbf{x}_{k:n|n} + \sum_{s=1}^{S}\mathbf{y}^s_{k:n}\right). \tag{73}$$

Table 3

Distributed ASD Filter	
Initialization	For $s = 1, \ldots, S$ compute $\left\{\left(\mathbf{x}^s_{k:n|k},\mathbf{P}^s_{k:n|k}\right)\right\}$
Prediction	As in Table 1, except that $\mathbf{Q}_{l|l-1}$ is replaced by $S\mathbf{Q}_{l|l-1}$ for all l.
Filtering	As in Table 1, with $\mathbf{z}_k = \mathbf{z}^s_k$ for each processing node s.
Fusion Rule	$\mathbf{x}_{k:n|k} = \mathbf{P}_{k:n|k}\sum_{s=1}^{S}\left(\mathbf{P}^s_{k:n|k}\right)^{-1}\mathbf{x}^s_{k:n|k}$
	$\mathbf{P}_{k:n|k} = \left(\sum_{s=1}^{S}\left(\mathbf{P}^s_{k:n|k}\right)^{-1}\right)^{-1}.$

Note that the ASDs in (70) and (71) are *not* based on the relaxed evolution model, i.e., they are optimal with respect to the local sensor data.

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APPENDIX: PRODUCT FORMULA

For matrices of suitable dimensions, the following formula for products of Gaussians holds:

$$\mathcal{N}(\mathbf{z};\mathbf{Hx},\mathbf{R})\mathcal{N}(\mathbf{x};\mathbf{y},\mathbf{P}) = \mathcal{N}(\mathbf{z};\mathbf{Hy},\mathbf{S})\begin{cases}\mathcal{N}(\mathbf{x};\mathbf{y}+\mathbf{W}\nu,\mathbf{P}-\mathbf{WSW}^\top)\\ \mathcal{N}(\mathbf{x};\mathbf{Q}(\mathbf{P}^{-1}\mathbf{y}+\mathbf{H}^\top\mathbf{R}^{-1}\mathbf{z}),\mathbf{Q})\end{cases} \tag{74}$$

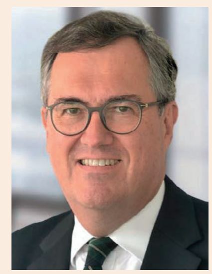
with the following abbreviations:

$$\nu = \mathbf{z} - \mathbf{Hy} \tag{75}$$

$$\mathbf{S} = \mathbf{HPH}^\top + \mathbf{R} \tag{76}$$

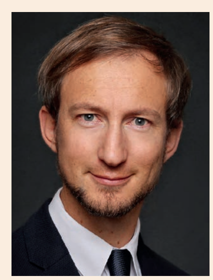
$$\mathbf{W} = \mathbf{PH}^\top\mathbf{S}^{-1} \tag{77}$$

$$\mathbf{Q}^{-1} = \mathbf{P}^{-1} + \mathbf{H}^\top\mathbf{R}^{-1}\mathbf{H}. \tag{78}$$



Wolfgang Koch studied physics and mathematics at the Aachen Technical Universit, Germany, where he earned a Dr. rer. nat. degree in theoretical physics. For many years, he was head of the Department of Sensor Data and Information Fusion at Fraunhofer FKIE, an institute of the Fraunhofer Society, the largest institution for applied research in Europe. On various topics within the area of sensor data and information fusion, he has published a well-referenced textbook on target tracking and sensor data fusion, 16 handbook chapters, and well above 200 journal and conference articles. He is one of the coeditors of the two volume handbook *Novel Radar Techniques and Applications*.

Wolfgang Koch is a fellow of the IEEE, where he serves for the *IEEE Transactions on Aerospace and Electronic Systems* and as a member of the board of governors of the Aerospace and Electronics Systems Society. In 2015, he was appointed an IEEE Distinguished Lecturer and chairman of the German IEEE AESS chapter. In 2013, he served as president of the ISIF. In his areas of expertise, he has been active in the NATO Science and Technology Organization for many years. At Bonn University, he holds a habilitation degree in applied computer science and regularly gives lecture series on sensor data and information fusion. In 2016, he was general co-chair of the IEEE ISF International Conference on Information Fusion, Heidelberg, Germany.



Felix Govaers received the diploma in mathematics and the Ph.D. degree with the title Advanced Data Fusion in Distributed Sensor Applications in computer science, both at the University of Bonn, Germany. Since 2009, he has worked at Fraunhofer FKIE in the Department of Sensor Data Fusion and Information Processing, where he was leading the research group distributed systems from 2014 to 2017. Currently, he is the deputy head of the department. The research of Felix Govaers is focused on data fusion for state estimation in nonlinear scenarios and in sensor networks, which includes track extraction, processing of delayed measurements, as well as the distributed Kalman filter and track-to-track fusion. Current research projects are in tensor decomposition–based approaches to multitarget tracking. He is also interested in advances in state estimation, such as particle flow and homotopy filters and the random finite set theory approaches.

Felix Govaers has been an active member of the International Society of Information Fusion (ISIF) community since 2008. He organized the ISIF-cosponsored Sensor Data Fusion Workshop in Germany for many years as the technical program chair. He is an active member of the ISIF board of directors since 2017. At FUSION 2016, he supported the organization team as the publication chair. Since 2014, he has served as an associate editor for the *IEEE Transactions on Aerospace and Electronic Systems* journal.

X. Rong Li and Roy Streit

FUSION 2017 Xi'an

JULY 10–13, 2017, XI'AN, CHINA

The International Society of Information Fusion (ISIF) organized its 20th annual flagship conference last July in the city of Xi'an, the ancient capital of the People's Republic of China. Xi'an Jiaotong University, the IEEE Aerospace and Electronic Systems Society, and the Chinese Society of Information Fusion co-organized the conference. From over 20 countries, 393 attendees came to Xi'an for academic exchange on information fusion–related research fields.

Group photo of FUSION 2017 attendees.

This diversity highlights the broad appeal of the conference and the international community supporting it. In the past two decades, the fusion community has been experiencing steady growth. FUSION 2017 had 12 tutorials, 269 presentations, and three keynote addresses, with a wide range of approaches, applications, and novel ideas covering all aspects of the field of information fusion research. A most impressive undertaking in FUSION 2017 was the 20 year special program, which is described in a separate article, "Twenty Years of Fusion."

FUSION 2017 was the first fusion conference in China. We briefly address the important organizational work of the complex conference events in this article.

TECHNICAL PROGRAM

All the conference activities occurred on a dedicated floor at the Wyndham Grand Hotel, which provided focus and convenience to leverage the richness of the technical program. Activities started with 12 tutorials on Monday, July 10, and the main conference was from Tuesday through Thursday.

Host cities of past 20 FUSION conferences.

The FUSION 2017 technical program committee included 243 members and was co-chaired by Vesselin Jilkov, Mitch Kokar, Brian La Cour, and Nagi Rao. It provided at least three expert reviews for each of the 369 submitted papers; many papers had more than three reviews. The result was 276 papers (with an acceptance rate of 74.8%) in a vibrant set of regular and special sessions, convened in eight breakout rooms. A complete list of all 35 sessions can be found at the conference website (www.fusion2017.org) and the EDAS system (http://edas.info/p23143).

Following the paper review process, the technical committee co-chairs assembled a set of 44 best-scoring papers and passed them on to the awards committee. The final selection of the awards was done by an awards committee headed by the two award co-chairs, Henk Blom and Chee-Yee Chong. The awards selection rules and process can be found at www.fusion2017.org. The best papers were the following:

JEAN-PIERRE LE CADRE BEST PAPER AWARDS

"Generalized Optimal Sub-Pattern Assignment Metric"
Abu Sajana Rahmathullah,[1] Angel Garcia-Fernandez,[2] Lennart Svensson[3]
[1]Zenuity AB, Sweden; [2]Aalto University, Finland; [3]Chalmers University, Göteborg, Sweden

FIRST RUNNER-UP

"Target Motion Analysis with Unknown Measurement Noise Variance"
Branko Ristic,[1,2] Xuezhi Wang,[1] Sanjeev Arulampalam[2]
[1]RMIT University, Australia; [2]Defence Science and Technology, Australia

SECOND RUNNER-UP

"Maximum Likelihood Detection on Images"
B. Balasingam,[1] Y. Bar-Shalom,[2] P. Willett,[2] K. Pattipati[2]
[1]University of Windsor, Canada; [2]University of Connecticut, USA

TAMMY BLAIR BEST STUDENT PAPER AWARDS

"Dual-Satellite Source Geolocation with Time and Frequency Offsets and Satellite Location Errors"
Chao Liu,[1] Le Yang,[2] Lyudmila Mihaylova[1]
[1]University of Sheffield, United Kingdom; [2]Jiangnan University, People's Republic of China

FIRST RUNNER-UP

"Student-*t* Process Quadratures for Filtering of Non-Linear Systems with Heavy-Tailed Noise"
Jakub Prüher,[1] Filip Tronarp,[2] Toni Karvonen,[2] Simo Särkkä,[2] Ondřej Straka[1]
[1]University of West Bohemia, Czech Republic; [2]Aalto University, Finland

SECOND RUNNER-UP

"Gradient-Based Recursive Maximum Likelihood Identification of Jump Markov Non-Linear Systems"
Andre R. Braga,[1] Carsten Fritsche,[2] Fredrik Gustafsson,[2] Marcelo Bruno[3]
[1]Federal University of Ceara, Quixadá, Brazil; [2]Linköping University, Sweden; [3]Aeronautics Institute of Technology, Brazil

Best student paper award.

The proceedings of all FUSION conferences so far (1998–2017) were distributed to all attendees on-site. The proceedings of FUSION 2017 have been published in IEEE Xplore and are posted on the ISIF website for FUSION 2017 attendees. Further details of the conference, including a photo gallery, can be found at www.fusion2017.org.

We are grateful to our plenary speakers whose talks brought conference attendees a rare mix of technical competence, experience, and passion for information fusion.

Plenary panel held in Wyndham Grand Hotel.

FUSION 2017's plenary sessions had two plenary talks and one plenary panel. Plenary talk speakers were:

- Yaakov Bar-Shalom, Target Tracking and Data Fusion: How to Get the Most out of Your Sensors (and Make a Living out of This),
- Chee-Yee Chong, Artificial Intelligence to Data Science: Challenges and Opportunities to Information Fusion,
- Alfonso Farina, Simon Godsill, Fredrik Gustafsson, Kathryn Laskey, Nageswara Rao, and Elisa Shahbazian, Data Fusion: Whither Now and Why, moderated by X. Rong Li. Invited Participants: Yaakov Bar-Shalom and Roy Streit.

In recognition of the meritorious contributions of Prof. Yaakov Bar-Shalom, FUSION 2017 had a special tribute workshop International Workshop on Fusion, Tracking, and Estimation—A Tribute to Professor Yaakov Bar-Shalom. Detailed information can be found at www.fusion2017.org.

Yaakov Bar-Shalom workshop.

SOCIAL ACTIVITIES

FUSION 2017 featured a number of social events. The guided tours to the Terracotta Army, the Old City Wall, and Mount Hua for attendees and their companions proved very popular. The icebreaker and welcome receptions were held at the conference venue.

Welcome reception.

The 7th Annual Fusion 5K Run was held at the Qujiangchi Relics Park. Twelve runners, including nine conference attendees and three family members joined the race.

Qujiangchi Relics Park (5K run).

The gala dinner was served on July 12, 2017, at the Huaqing Aegean International Hot Spring Resort. The evening included a full-course dinner, toasts by general co-chairs of FUSION 2017 and Lyudmila Mihaylova (ISIF president), an award ceremony for best papers and best student papers, and an award ceremony for the 20 year special program for FUSION conferences.

Gala dinner.

After the banquet, conference attendees went to a famous attraction, Huaqing Pool, to watch the show *Song of Everlasting Sorrow*. Many conference attendees claimed it was a "once-in-a-lifetime experience."

The *Song of Everlasting Sorrow* show.

ORGANIZATION

FUSION 2017 was a great success: a large number of submissions, many high-quality accepted papers, high attendance levels, a week packed with technical and cultural events, and a healthy profit for ISIF.

ACKNOWLEDGMENTS

The driving force behind the FUSION conferences is the information fusion community. We are grateful to the organizing committee, past organizers who helped us, the ISIF Board of Directors, all volunteers, and everyone for their contributions to a successful FUSION 2017.

ISIF-Sponsored Events and Workshops

Felix Govaers and Wolfgang Koch

IMPRESSIONS OF THE 11TH IEEE AESS SYMPOSIUM ON SENSOR DATA FUSION—TRENDS, SOLUTIONS, APPLICATIONS (SDF 2017), OCTOBER 10–12, 2017, BONN, GERMANY

Before any thoughts of technical realization or scientific reflections on it, all living creatures perform Sensor Data Fusion (SDF): they combine sensations from mutually complementary sense organs with their past experiences and the communications they receive from other creatures. By doing so, they generate "situation pictures" of their particular environment, the very basis for behaving appropriately to reach certain goals or to avoid harm.

As a key activity of the International Society of Information Fusion (ISIF) community, Sensor Data Fusion tries to understand "natural orientation" of creatures in their environment, to automate the generation of situation pictures as far as possible, and to extend them far beyond "natural" capabilities.[1] The megatrends towards miniaturized sensors, autonomously operating mobile platforms as well as navigation, communication, and computing are technological driving factors for developing advanced algorithms for Sensor Data Fusion. These algorithms enable the design of "cognitive tools" for enhancing our mental capabilities to understand vast sensor data streams in analogy to mechanical tools that enlarge our physical strengths. Needless to say, Sensor Data Fusion is a key technology in many defence and civil applications.

The ISIF symposium "Sensor Data Fusion—Trends, Solutions, Applications" (SDF 2017) took place on October 10–12, 2017, at the University of Bonn, Germany, and was the 11th in a row of small conferences that have been technically cosponsored by the ISIF and the Institute of Electrical and Electronics Engineers (IEEE) Aerospace and Electronics Systems Society (AESS). Designed as a small scale annual conference with a very personal atmosphere, it is complementary to the large ISIF International Conferences on Information Fusion, where the global fusion community regularly meets at varying locations. All workshop papers that have been accepted in a peer-reviewed process are made globally accessible via IEEE Xplore.

The SDF Symposium was created to reach three goals: With 24 high-quality oral presentations in comfortable time slots of 30 minutes, it firstly provides insight into most recent developments in Sensor Data Fusion, addressing methodological advances as well as innovative applications and fostering discussions. Secondly, a keynote lecture enables more comprehensive understanding of upcoming topics. At SDF 2017, Lennart Svensson from the Chalmers University of Technology, Göteborg, Sweden, a leading researcher in Sensor Data Fusion, delivered a highly inspiring and enthusiastically presented lecture on "*Sets of Trajectories, Conjugate Prior Densities and Metrics: Three General Tools for Multi-Target Tracking*." Last but not least, the SDF Symposium is a sort of "family meeting" of "fusionaries" stimulating networking and personal interaction by an "icebreaker" dinner in a traditional German beer-house on the first day and a workshop dinner at the second day, which is traditionally opened by a musical event.

SDF 2017 was jointly organized by Wolfgang Koch, Fraunhofer FKIE/University of Bonn, and Peter Willett, University of Connecticut, acting as executive co-chairs. Technical Program Chair was Felix Govaers, Fraunhofer FKIE, while Stefano Coraluppi, Systems and Technology Research, USA, served as a Publicity Chair. Seven technical sessions addressed *Advances*

[1] See e.g., Koch. W. *Target Tracking and Sensor Data Fusion—Methodological Framework and Selected Applications. Mathematical Engineering Series*. Springer, 2014.

SDF Symposium is represented in social media for the first time.

Felix Govaers, Roy Streit, Lennart Svensson, Chee-Yee Chong, Stefano Coraluppi, and Wolfgang Koch (from left to right). The ISIF banner can be seen in the background.

Chee-Yee Chong talking on 40 years history of distributed estimation.

Lennart Svensson giving his keynote speech of 90 minutes with great depth and broad applications.

in Methodology, *Indoor Tracking and Navigation, Models and Estimation Theory, Classification and Detection, Radar and Sonar Applications, Advances in Random Finite Set Filters,* and *Higher Level Fusion and Fusion Architectures*. There were about 60 participants with a diverse mixture of interested people from industry, academia and research institutes. The audience was international (Italy, France, the Netherlands, Great Britain, and Greece for instance) but the majority were from Germany due to the local attraction. The audience stayed in a single group, which often resulted in interesting and feisty discussions.

The "Best Paper Award" was won by Manuel Stübler, Stephan Reuter, and Klaus Dietmayer (*A Continuously Learning Feature-based Map using a Bernoulli Filtering Approach*), who wrote on a new strategy for Bernoulli-filter based feature estimation for simultaneous localization and mapping applications. Among other talks of high interest were Roy Streit's presentation on Analytical Combinatorics, which was used to present the probability generating functional of the multi-hypothesis tracking family. Great attention was given to Chee-Yee Chong with his presentation on 40 years of distributed estimation history. Also highly convincing was the talk of Umut Orguner on fast optimization of weights for covariance intersection methods.

We will continue our series regularly in 2018 with the upcoming SDF Symposium. More information on this and future SDF workshops can be found at http://fkie.fraunhofer.de/sdf2018.

ISIF-Sponsored Events and Workshops

Mihai Florea and Elisa Shahbazian

7TH CANADIAN TRACKING AND FUSION GROUP (CTFG) WORKSHOP, NOVEMBER 6–7, 2017

The Canadian Tracking and Fusion Group (CTFG) was established in 2010 with the objective of advancing awareness of information fusion and the more recent objective to address real-world problems, as well as to encourage collaboration among government, industry, and academia on problems of common interest related to information fusion.

The seventh annual workshop was held at the Les Suites Hotel in Ottawa, Canada, on November 6–7, 2017. The workshop was well attended, with more than 60 participants from government, industry, and academia. The format of the workshop was a single, oral track, divided into four special talks by invited speakers and 28 regular talks, divided into four tracking sessions and four fusion sessions.

The first invited speaker, Mr. Eric Fournier, Director General S&T Strategic Decision Support, provided information about the Innovation for Defence Excellence and Security Program, which is an augmentative approach to accessing innovation, allowing Canada's military to better tap into extraordinary talent and ingenuity resident in Canada.

Later on that first day, Dr. Llinas, the second invited speaker, talked about the knowledge requirements for the design of distributed multisensor multitarget tracking systems. The first day continued with four tracking-related sessions, on the following topics:

- Sensor and resource management
- Detection and tracking
- Clutter, estimation, and fusion 1 and 2

The first invited speaker of the second day was Dr. Roy Streit who presented analytic combinatorics in tracking and information fusion. The second invited speaker of this day was Mr. Srikanth, associated with the Build in Canada Innovation Program, which is a R&D procurement program aimed at procuring, testing, and evaluating R&D precommercialized goods and services in the late stage development.

The second day of the workshop continued with four fusion-related sessions on the following topics:

- System design and concepts
- Optimization and planning
- High-level fusion 1 and 2

Dr. Hossein Chahrour from Carleton University (photo by Janice Lang).

The presentations and abstracts of all invited and regular talks have been distributed to the participants of the workshop and can be provided, upon request, to all International Society of Information Fusion (ISIF) members. More information about the CTFG Workshop 2017 can be found on the CTFG website at www.ctfg.ca. After six years, the CTFG website was redesigned with a WordPress template. Our Canadian community of tracking and fusion is growing, and we are pleased to note that we continue to have greater exposure year after year.

At the end of the two-day workshop, the following two organizational meetings took place:

1. Planning the organization of CTFG: The CTFG organizing committee members expressed their overall impressions (lessons learned) about the technical program and the new venue that was selected for the first time for CTFG 2017. The committee also nominated the chairs for CTFG 2018. Melita Hadzagic and Steven Horn will fulfill the role of general co-chairs for the organization of CTFG 2018.
2. A meeting of the local organizing committee for FUSION 2019: This was the second meeting of the committee after the CTFG 2016. The committee reviewed the status of each item introduced in 2016, including the technical program, with the plenary speaker selection, the tutorials and the special sessions, the organization, the committee, the venue, and the options for entertainment (the contracts to be signed and the partnership options with IEEE). After the meeting, some of the FUSION 2019 organizers met with the management for the venue of the conference at the Shaw Centre (Ottawa), agreed on conditions, and secured it.

THE 2017 CTFG WORKSHOP ORGANIZING COMMITTEE

Elisa Shahbazian (general chair), OODA Technologies

Mihai Florea (general co-chair), Thales Canada

Jack Ding, DRDC Ottawa

Tony Ponsford, consultant

Bhashyam Balaji, DRDC Ottawa

Rami Abielmona, Larus Technologies

Rafael Falcon, Larus Technologies

Anne-Laure Jousselme, NATO Centre for Maritime Research and Experimentation

Steven Horn, DRDC CORA

Thia Kirubarajan, McMaster University

Ratnasingham Tharmarasa, McMaster University

Sreeraman Rajan, Carleton University

The great success of this workshop was not possible without the contribution of our amazing organizing committee and of our sponsors (ISIF, IEEE Ottawa Section and its supporting chapters, Thales Canada, Larus Technologies, Trackgen, OODA Technologies, and Ottawa Tourism).

CTFG 2017 participants (photo by Janice Lang).

ISIF WORKING GROUPS

Paulo Costa

ISIF WORKING GROUPS: BE ENGAGED!

According to its stated vision, the International Society of Information Fusion (ISIF) is the premier global information resource for multidisciplinary approaches for theoretical and applied information fusion techniques. As such, the Society provides its community with a number of activities that aim at fulfilling the six main thrusts of its mission: advocate, serve, communicate, educate, integrate, disseminate, and collaborate.

Most people would easily recognize the FUSION conference series and the *Journal of Advances of Information Fusion* as major initiatives sponsored by the Society, while its own members might also list the membership services as another great activity supporting ISIF's mission. Although the Society is actually involved in many more activities that support its mission, there is a fourth key component within its portfolio of benefits—one that many of us are not even aware of—the ISIF Working Groups (WGs). This brief article is meant to provide an overview of what ISIF WGs are and how beneficial they are to our community.

FOSTERING GROUPS OF INTEREST

Information fusion is as fascinating as it is broad. After all, its definition accommodates a plethora of techniques and research topics that are key to ISIF's vision. Some of those topics have already reached maturity, and we, as stellar researchers and practitioners in our ranks, bring new advances every year. However, there are situations in which topics of interest to the overall science of information fusion need a little help to reach maturity and become a regular source of success stories. These include new ideas that must be developed, specific research problems in need of some structuring, groups of interest that must gather critical mass to thrive, and others that would need a kick-start before getting up to speed. WGs are an amazing tool to address this problem, and it is relatively easy to create one.

CURRENT AND PAST ISIF WORKING GROUPS

WGs are by no means a new ISIF feature. In fact, the Society already has a number of positive experiences in this area, which are listed in the following.

The Multistatic Tracking WG (MSTWG) was founded in 2004 and became an ISIF WG in 2007, with the objective of promoting collaboration among its members in multisensor fusion and tracking, and a focus on multistatic sonar and radar. This collaboration has been achieved through 17 regular meetings, five teleconferences, 11 special sessions at conferences, and the analysis of seven common data sets. The MSTWG ended its activities in July 2016, and it is fair to say that the group achieved excellent results and was very influential in its field.

The Fusion Process Model and Frameworks WG (FPMFWG) was created in 2010 to promote discussion and consensus development on the characterization and specification of a

canonical fusion process, major fusion functions (e.g., situational estimation), and related software frameworks. At inception, it was clear that this was an ambitious charter, especially in the sense of achieving consensus on such process and framework specifications. As a result, the basic goal for the FPMFWG was to become the agent or mechanism for promotion of lively collegial discussion and archiving of alternative ideas and models and serve to keep this topic in front of the community. The FPMFWG was decommissioned in 2015, and its activities continued separately as a discussion group.

The Evaluation of Techniques for Uncertainty Representation Working Group (ETURWG) was created in 2011 with the intent of bringing together experts, researchers, and practitioners from the fusion community to leverage the advances and developments in the area of evaluation of uncertainty representation to address the problem of assessing uncertainty representation and reasoning approaches for high-level information fusion systems. The group aims at establishing features required for any quantitative uncertainty representation to support the exchange of soft and hard information in a net-centric environment, developing a set of use cases involving information exchange and fusion requiring reasoning and inference under uncertainty, and defining evaluation criteria supporting unbiased comparisons among different approaches applied to the use cases.

ETURWG remains active, and as of this writing, it has conveyed 101 meetings (mostly telecons, averaging 1 h), published 43 papers in the seven special sessions, and created a draft of an evaluation framework.

WHY AND HOW TO BE ENGAGED

The principal advantage to ISIF for the formation of a WG is an enlargement of its active base of researchers engaged in collaborative efforts and supporting ISIF's mission and activities. Currently, there are a couple of groups that can potentially engage.

The advantages members have when forming an ISIF WG include the following:

- Official recognition and status as an ISIF WG.
- Minimal bureaucratic overhead. ISIF asks that each group report in writing or with a brief presentation to the annual meeting of the ISIF board of directors. The group is free to manage its membership, meeting schedule, and activities.
- Support for WG meetings. It is customary (though not required) that each WG hold a day-long meeting in conjunc-

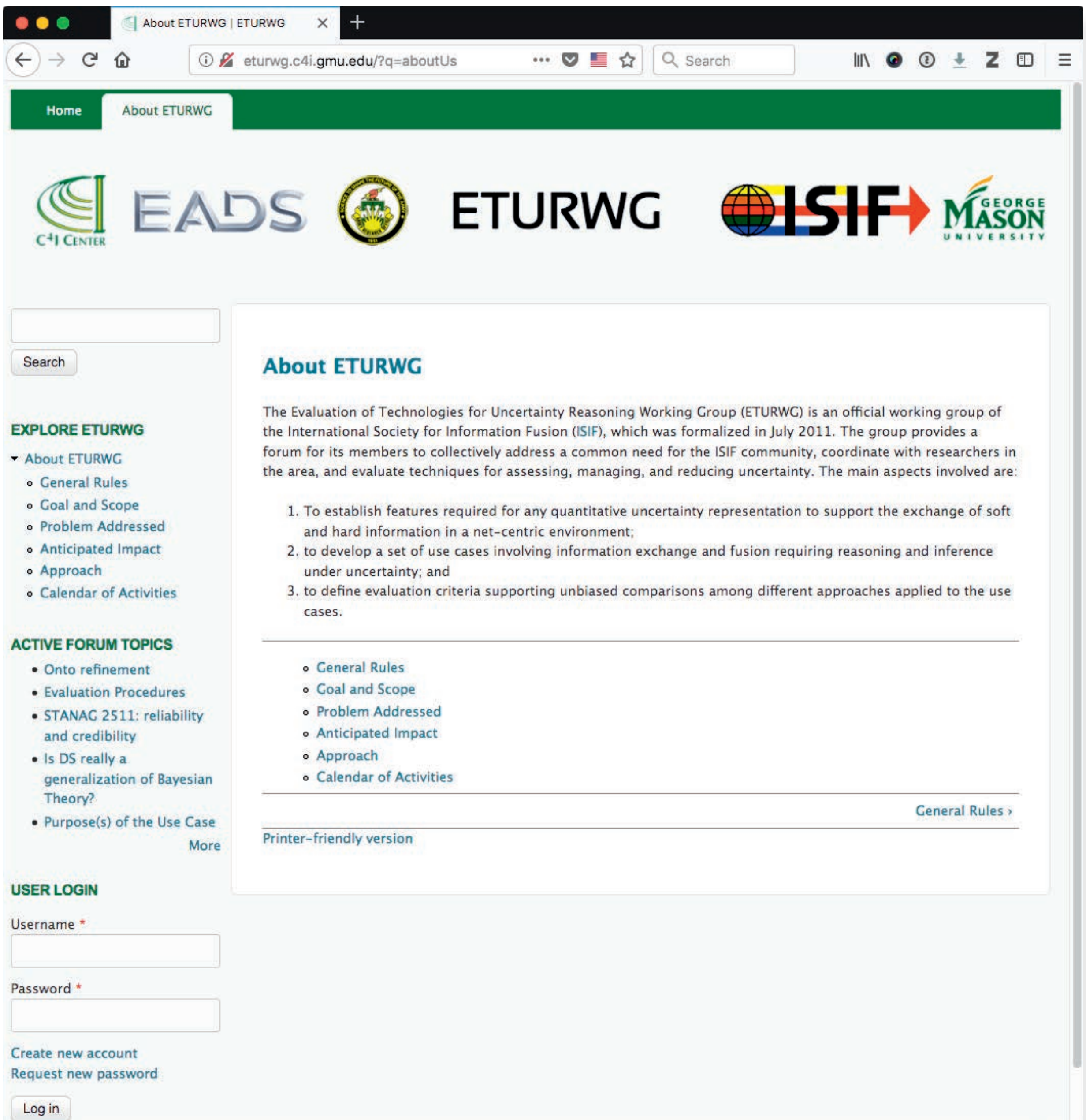
tion with the annual FUSION conference. The meeting is generally held on conference premises, on the day immediately preceding or following the conference. The cost of the meeting is usually covered under the conference budget.

- ► Conference special sessions. Official ISIF WGs are encouraged to hold a special session on their topic as part of the annual fusion conference. Approval of the special session proposal, while not guaranteed, is highly likely.

Any ISIF member can submit an application for forming a WG, and all ISIF members can participate in the WGs. The application process is straightforward and basically involves crafting a proposal that explains what the goals of the group are, how it benefits the IF community, and other details that would then be presented to the ISIF Board of Directors.

Once formed, the logistics, level of commitment, modus operandi, and other aspects of the WG are entirely at the discretion of their members, and the coordination with ISIF will be the responsibility of the WG chairs.

WGs are a powerful tool that ISIF brings to its members and a key part for the Society to realize its vision. It is available to all of us and constitutes a wonderful way of developing ideas and contributing to the advancement of our community. If you are interested, send an e-mail to the ISIF vice president for WGs (contact available at http://isif.org/working-groups/isif-working-groups).



The ETURWG website.

Yifang Shi and Yunfei Guo

EVENT REPORT

THE FIRST WEST LAKE WORKSHOP ON TARGET TRACKING AND INFORMATION FUSION, MAY 28–30, 2018, HANGZHOU, ZHEJIANG, CHINA

Nearly 100 participants from industry, research institutes, and academia from seven countries and four continents attended this event. The workshop was sponsored jointly by the Information Fusion Branch of Chinese Society of Aeronautics and Astronautics and the Hangzhou Dianzi University (HDU), and it was organized by the HDU School of Automation through the Overseas Expertise Introduction Center for Discipline Innovation (111 Center: the Programme of Introducing Talents of Discipline to Universities) in Perception and Control of Cyber-Physical Systems and the Fundamental Science on Communication Information Transmission and Fusion Technology Laboratory.

The workshop's key objective was to provide an open platform for academics, researchers, and practitioners to present the latest developments on a wide range of topics in target tracking and information fusion, as well as to trigger in-depth discussions on state-of-the-art concepts and the future of these fields. To foster international collaboration and to encourage student participation, this workshop was free of any registration fees. The technical program included 12 in-depth talks on various aspects of target tracking and information fusion given by prominent researchers from China and abroad. A panel discussion on a current topic of interest was also held at the end of each day to encourage open discussion and questions and to provide some vision to students about the trends in the future of tracking and fusion.

The workshop began with the opening remarks by Prof. Thia Kirubarajan from McMaster University, Canada, the general co-chair of the workshop. The remarks were followed by the welcome speech by Prof. Ning Zheng, vice president for International Cooperation at HDU, who set the tone for the workshop by quipping "data fusion is a 100 flowers growing together" to emphasize the need for innovation through collaboration. The first technical talk was by Dr. Roy Streit

Attendees of the workshop.

from the University of Massachusetts–Dartmouth, USA, on unifying multitarget tracking and high-level information fusion through analytic combinatorics. Next, Prof. Zhanshen Duan from Xi'an Jiaotong University, China, spoke about the analysis, design, and estimation of constrained dynamic systems. With an eye to the practical applications, Prof. Murat Efe from Ankara University, Turkey, and Prof. Baofeng Guo from HDU talked about data fusion for positioning and navigation and about hyperspectral band selection and image classification, respectively. Dr. Alfonso Farina, Italy, based on his vast experience in the field, talked about the trends in target tracking in view of recent advances in sensing and computing technologies. Dr. Ratnasingham Tharmarasa from McMaster University, Canada, then discussed the challenges in target tracking and information fusion with application to autonomous vehicles and intelligent transportation. The first day of the workshop concluded with a four-member panel discussion, titled "Predicting the Future of Target Tracking," hosted by the Prof. Kirubarajan, which discussed the various applications, theoretical frameworks, and the technological advances that are shaping up the field of target tracking.

The second day of the workshop began with a talk on computationally efficient multiple detection multitarget tracking algorithms by Prof. Taek Lyul Song from Hanyang University, South Korea. This was followed by a talk on state estimation with constraints by Prof. Gongjian Zhou from the Harbin Institute of Technology, China. Next, Prof. Johan Pieter de Villiers from the University of Pretoria, South Africa, talked about joint classification, association, tracking and behavioral analysis with application to counterpoaching, stock theft mitigation, and border surveillance. Then, Prof. Quanhua Liu from the Beijing Institute of Technology, China, talked about applying wideband radar for target detection and tracking. Dr. Eloi Bosse from Expertise Parafuse Inc., Canada, spoke about big data and Internet-of-Things for tracking and gating in a complex world of interconnections. He was followed by Prof. Feng Yang from Northwestern Polytechnical University, China, who spoke about target tracking based on random finite set

Talks and panel discussions: counterclockwise from the upper left, Thia Kirubarajan (general co-chair), Dongliang Peng (organizational chair), Roy Streit, Zhansheng Duan, Murat Efe, Baofeng Guo, Alfonso Farina, Yunfei Guo (organization team member), Ratnasingham Tharmarasa, Taek Lyul Song, Gongjian Zhou, Johan Pieter de Villiers, Quanhua Liu, Anke Xue (general co-chair), Eloi Bosse, and Feng Yang, along with the two panels in the middle.

and machine learning. Finally, a six-member panel discussion, titled "Tracking to Learn and Learning to Track," was held with a focus on the interplay between the emerging field of artificial intelligence and the traditional field of model-based target tracking.

Marco Polo once said, “Hangzhou is without a doubt the finest and most splendid city in the world.” The third day of the workshop was reserved for social activities along the West Lake and the surrounding hills in Hangzhou so that the visitors could validate Marco Polo’s observations.

The organizing team and volunteers from the Fundamental Science on Communication Information Transmission and Fusion Technology Laboratory at HDU deserve the appreciation of the participants for a finely organized event with generous financial support.

In view of the large audience for the event (about 100 participants), the deep discussions it offered, and potential collaborations it fostered, the First West Lake Workshop on Target Tracking and Information Fusion can be considered as a very fruitful event in advancing interest and the state-of-the-art concepts in these fields. On the basis of the success of this first workshop, the plan is to make it into a biennial event to sustain the effort and ensure the benefits of international collaboration. We welcome all interested researchers to participate in the Second West Lake Workshop on Target Tracking and Information Fusion planned for May 2020 in splendid Hangzhou.

Book Review

Jonathan Legg

Context-Enhanced Information Fusion: Boosting Real-World Performance with Domain Knowledge

Lauro Snidaro, Jesus Garcia, James Llinas, and Erik Blasch, editors

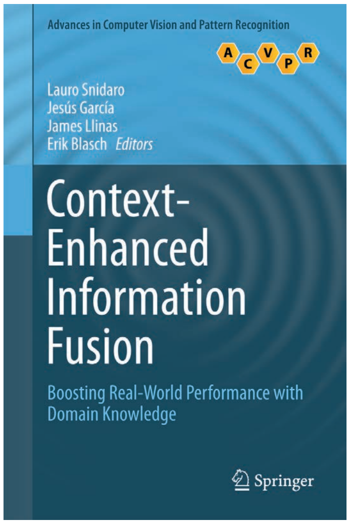
Springer, 2016
DOI 10.1007/978-3-319-28971-7

This is an exciting book. It is large (703 pages and 25 chapters), broad in scope, and covers a lot of material to a useful depth. It is also well organized and describes the state-of-the-art in methods for incorporating background knowledge into information fusion problems.

Information fusion is the process of taking multiple pieces of information, from single or multiple sources, and combining them to estimate the underlying processes of interest. These could be the trajectories of vehicles seen by radars, or a developing situation involving ground forces, for example. Estimation problems such as these combine information from sensors with a priori background information, such as a model of how vehicles move. But this motion model could be usefully constrained through knowledge of the likely types of vehicles being tracked, potentially leading to greater tracking accuracy.

This book discusses the use of context in information fusion across both the Joint Directors of Laboratories (JDL) spectrum of information fusion (for example, [1]) and across hard and soft data fusion (that is, fusing "physics-based" data such as from radars with "human-sourced" data such as from Twitter). While it provides several explanations of "context" in information fusion, the term essentially refers to the use of "structural knowledge of the scene, known a priori relationships between the entities and the surrounding environment, dynamic scenarios necessary to interpret or constrain the system output, and user preferences, social norms and cultures when estimating the situations of interest for the domain." In slightly more depth, there are discussions of "context of" ("background context, which provides a more general and stable environment") and "context for" ("secondary characteristics, which can be more dynamic") (chapter 2). Other examples of context include road networks and driver behavior, which represent information that should have an effect on the output of the information fusion system, but would not normally be explicitly factored into a textbook Kalman filtering problem.

Intuitively, contextual information should be particularly valuable for improving the performance of a fusion system when you only have access to a finite volume of sensor data, because it can be thought of as another source of measurements. In the extreme, it may also help solve problems that otherwise could not be solved due to a lack of information. "Challenging scenarios where context can play a role include: object labelling, track correlations/stitching through dropouts, and activity recognition" (chapter 18, p. 479).



I find there are two dangers with books where each chapter is written largely by different authors: that each chapter introduces the topic in its own way, and that it is unusual for many chapters to go beyond hand-waving, providing enough information for the enthusiastic reader to apply the material. This book does a good job of defining the problem and maintaining consistency across the various perspectives (although one feels that the definition of "context" depends on the context). Some chapters provide an overview of some algorithms, but this is not a "how-to" book. It does, however, provide a useful catalogue of references to the literature.

An outline of the book follows, highlighting some areas that I find particularly interesting:

- **Foundations** (chapter 1), where the editors attempt to impose order through definitions and background in a book with many disparate contributors and applications;
- **Concepts of context for fusion** (chapters 2–6), with background material that includes patterns of life and anomaly detection as context (noting that this topic is also mentioned elsewhere in the book), and chapter 3 discussing uncertainty in contextual information by treating it as a source of uncertain data;
- **Systems philosophy of contextual fusion** (chapters 7–10), with fusion system architectures, in particular middleware to handle context-related information exchanges (chapters 8, 9);
- **Mathematical characterisation of context** (chapters 11–15), with context incorporated into low-level tracking, such as the incorporation of knowledge of road networks (section 12.4.3, with ground target tracking also discussed in chapters 4 and 22); and learning approaches that estimate the context from the data (chapter 15). A variety of approaches for handling context are discussed in these chapters.
- **Context in hard/soft fusion** (chapters 16–19) additionally discusses multilevel fusion (in a JDL sense), with

context as a binding element (chapter 16), and chapter 17 suggests Battle Management Language to communicate both data and contextual information between data fusion levels, with some discussion of uncertainty representations;

- **Applications of context approaches to fusion** (chapters 20–24) discusses a logic-based knowledge base to assist with video tracking (chapter 23); and
- **Context in robotics and information fusion** (chapter 25) appears to be a very good summary of sensor fusion in the world of robotics, with some discussion of context representation approaches including logic-based and probabilistic approaches (section 25.2.2).

I also have an interest in a context-enhanced reasoning system that operates through interactions between a Bayesian process and a knowledge base, or vice versa. (This is the motivation for the "middleware" referred to in chapters 8 and 9.) Such ideas lead to the question of how uncertainty could be incorporated into knowledge bases, and this is a topic that I feel could have been expanded on further. The book mentions Markov logic networks (e.g., section 4.2 on contextual tracking, and 16.4 on design directions for context-aware systems) and Bayesian networks (e.g., section 3.4 regarding ontologies, section 25.2.2.3 on probability-based representations), with details left to the references, which are generally in the fusion literature rather than comprehensive texts (e.g., [2], [3]). The broader area of probabilistic programming has been undergoing dramatic changes in recent years (e.g., [4]), so its absence is not a major concern.

If you would like to understand contextual information and how your data fusion system might benefit from it, this book should make very interesting reading.

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ISIF Awards

Dale Blair

2018 ISIF AWARDS

In order to encourage excellence in the field of information fusion, the International Society of Information Fusion (ISIF) sponsors two awards. The first and most prominent ISIF award is the ***ISIF Yaakov Bar-Shalom Award for a Lifetime of Excellence in Information Fusion***, given to recognize a researcher or engineer for outstanding contributions to the field of information fusion throughout their career. The second is the ISIF Young Investigator Award for Contributions to Information Fusion that is given to encourage individual effort and foster increased participation by developing researchers and engineers in the field of information fusion.

Karl Granstrom, 2018 ISIF Young Investigator, with Yaakov Bar-Shalom, Dale Blair, and Lyudmila (Mila) Mihaylova, 2018 ISIF President.

The 2018 winner of the ISIF Young Investigator Award for Contribution to Information Fusion is Karl Andreas Granström. The basis for Dr. Granström's selection for the award is his contributions to the theory and practice of tracking multiple extended targets. Lennart Svensson nominated Dr. Granström, and Ba-Ngu Vo, Fredrik Gustafsson, Peter Willett, and Umut Orguner gave references for the award. Karl is a Postdoctral Research Fellow with the Department of Electrical Engineering in Chalmers University of Technology in Sweden. He received the Ph.D. degree in electrical engineering from Linköping University in 2012.

Dr. Pramod Kumar Varshney was selected as the recipient of the 2018 ***ISIF Yaakov Bar-Shalom Award for a Lifetime of Excellence in Information Fusion***. Dr. Varshney's contributions to the theory and application of information fusion, detection, estimation, and his leadership in the formation and growth of ISIF are the basis for his selection of the award. Dr. Ruixin Niu of Virginia Commonwealth University nominated Dr. Varshney, and Yaakov Bar-Shalom, Kuo-Chu Chang, Lance Kaplan, and Peter Willett served as endorsers of the nomination. Dr. Varshney is a Distinguished Professor in the Center for Advanced Systems and Engineer at Syracuse University in New York. He is an IEEE Fellow and recipient of the IEEE Third Millennium Medal in 2000.

Nominations for the ***ISIF Yaakov Bar-Shalom Award for a Lifetime of Excellence in Information*** and the ISIF Young Researcher Award are due to the Chair of the ISF Awards committee before January 31 in the year of the award. The ISIF Awards Committee is responsible for selecting awardees from the nominees submitted by ISIF members. The members of the 2018 ISIF Awards Committee were William Dale Blair, Chair, Yaakov Bar-Shalom, Craig Agate, Elisa Shahbazian, and Paulo Costa.

Promod Varshney, 2018 Awardee of Yaakov Bar-Shalom Award for a Lifetime of Excellence in Information Fusion, with Dale Blair, Yaakov Bar-Shalom, and Lyudmila (Mila) Mihaylova, 2018 ISIF President.

FUSION Conference Awards

Fredrik Gustafsson and Jason Williams

FUSION 2018 BEST PAPER AWARDS

ISIF 2017 JEAN-PIERRE LE CADRE BEST PAPER AWARD

"Scalable Magnetic Field SLAM in 3D Using Gaussian Process Maps"
Manon Kok, Delft University of Technology, The Netherlands and Aalto University, Finland, and Arno Solin, Aalto University, Finland

The winner of the Jean-Pierre Le Cadre Award for Best Paper considers the problem of three-dimensional simultaneous localization and mapping (SLAM) using magnetic field measurements. The area being mapped is divided into overlapping hexagonal regions; within each region, the magnetic field is mapped using Gaussian processes, with efficiency aided through a truncated Eigendecomposition of the covariance kernel. A Rao-Blackwellised particle filter maintains samples of the history of sensor position and pose, each accompanied by a Gaussian distribution representing the map. An impressive experiment is presented using odometry and magnetic field data recorded from a standard iPhone, demonstrating the value of the magnetic field measurements for aiding position estimation.

FIRST RUNNER-UP

"On Integrating Human Decisions with Physical Sensors for Binary Decision Making"
Thakshila Wimalajeewa and Pramod Varshney, Syracuse University, USA, and Muralidhar Rangaswamy, Air Force Research Labs, USA

SECOND RUNNER UP

"Total Belief Theorem and Generalized Bayes' Theorem"
Jean Dezert, French Aerospace Lab, France, Albena Tchamova, Inst. of I&C Tech, Bulgaria, and Deqiang Han, Xi'an Jiaotong University, China

ISIF 2017 TAMMY BLAIR BEST STUDENT PAPER AWARD

"Remote State Estimation with Data-Driven Communication and Guaranteed Stability"
Xiaolei Bian, X. Rong Li, and Vesselin P. Jilkov, University of New Orleans, USA

The winner of the Tammy Blair Award for Best Student Paper considers the problem in which a remote sensor iteratively transmits information across a constrained communication channel. An information push mechanism is described, whereby, using its own local estimator, the sensor determines when it is worthwhile contributing its new information based on the magnitude of the innovation. An estimator is constructed for the receiver utilizing the cumulative innovation, alongside the knowledge that previous innovation magnitudes were too small to warrant communication, such that the lack of transmission itself conveys information. A stability property of the estimator is proven.

FIRST RUNNER-UP

"Information Decorrelation for an Interacting Multiple Model Filter"
Duygu Acar, ASELSAN Inc, Turkey and Umut Orguner, Middle East Technical University, Turkey

SECOND RUNNER UP

"Multi-Sensor Multi-Object Tracking with Different Fields-of-View Using the LMB Filter"
Suqi Li, University of Electronic Science and Technology, China, Giorgio Battistelli, Luigi Chisci, Università delgi Studi di Firenze, Italy, and Wei Yi, Bailu Wang, and Lingjiang Kong, University of Electronic Science and Technology, China

The selection process for the awards was based on the following steps:

- Papers co-authored by FUSION 2018 Chairs are not eligible for awards and these were ruled out.
- A long list of 50+ papers was created based on the reviewers' scores and comments.
- Two short lists with 10 and 11 papers were selected based on a combination of good review scores (>4.2), award recommendations (59 in total!) and insightful review comments.
- Based on the short lists, an external award committee with eight members was selected.
- The award committee was split into two groups to minimize conflicts of interests.
- Each group ranked all papers in their respective short list.
- Thereafter, a free discussion followed on the final ranking list.

The competition was hard, and it was not easy to rank the papers in each category. However, in the end, the two winners were singled out as outstanding contributions. The award committee consisted of Sanjev Arulampalam, Erik Blasch, Felix Govaers, Gustaf Hendeby, Mahendra Mallick, Simo Särkkä, Elisa Shahbazian, and Ondrej Straka, and the award chairs are very thankful for their thorough work despite the short time span.

X. Rong Li

BEST PAPER AND BEST STUDENT PAPER AWARDS, FUSION 2004–2017

The Jean-Pierre Le Cadre Award is intended to recognize excellence among researchers and scientists in information fusion, which was the core motivation behind Jean-Pierre Le Cadre's career. The Jean-Pierre Le Cadre Award is given for the best paper of the annual International Conference on Information Fusion (FUSION) and often includes a signed copy of a recently published book in the area of information fusion.

The Tammy L. Blair Award is intended to encourage the involvement of young researchers and scientists in information fusion. It honors Tammy L. Blair's commitment to the International Society of Information Fusion. The Tammy L. Blair Award is given to recognize the best student papers at the annual International Conference on Information Fusion (FUSION) and includes cash prizes and travel grants. Awardees are often given a signed copy of a recently published book in the area of information fusion.

Both awards are managed by the organizing committee for the annual conference. Past recipients are summarized in the following.

2017

JEAN-PIERRE LE CADRE BEST PAPER AWARD

"Generalized Optimal Sub-Pattern Assignment Metric"
Abu Sajana Rahmathullah,[1] Angel Garcia-Fernandez,[2] Lennart Svensson[3]
[1]Zenuity AB, Sweden; [2]Aalto University, Finland; [3]Chalmers University of Technology, Gothenburg, Sweden

FIRST RUNNER-UP

"Target Motion Analysis with Unknown Measurement Noise Variance"
Branko Ristic,[1,2] Xuezhi Wang,[1] Sanjeev Arulampalam[2]
[1]RMIT University, Melbourne, Australia; [2]Defence Science and Technology, Australia

SECOND RUNNER-UP

"Maximum Likelihood Detection on Images"
Balakumar Balasingam,[1] Yaakov Bar-Shalom,[2] Peter Willett,[2] Krishna Pattipati
[1]University of Windsor, Canada; [2]University of Connecticut, Storrs, USA

TAMMY BLAIR BEST STUDENT PAPER AWARDS

"Dual-Satellite Source Geolocation with Time and Frequency Offsets and Satellite Location Errors"
Chao Liu,[1] Le Yang,[1,2] Lyudmila Mihaylova[1]
[1]University of Sheffield, United Kingdom; [2]Jiangnan University, People's Republic of China

FIRST RUNNER-UP

"Student-*t* Process Quadratures for Filtering of Non-Linear Systems with Heavy-Tailed Noise"
Jakub Prüher,[1] Filip Tronarp,[2] Toni Karvonen,[2] Simo Särkkä,[2] Ondřej Straka[1]
[1]University of West Bohemia, Pilsen, Czech Republic; [2]Aalto University, Finland

SECOND RUNNER-UP

"Gradient-Based Recursive Maximum Likelihood Identification of Jump Markov Non-Linear Systems"
Andre R. Braga,[1] Carsten Fritsche,[2] Fredrik Gustafsson,[2] Marcelo G. S. Bruno[3]
[1]Federal University of Ceara, Brazil; [2]Linköping University, Sweden; [3]Aeronautics Institute of Technology, Brazil

2016

JEAN-PIERRE LE CADRE BEST PAPER AWARDS

"Model-Based Data-Driven Approach for Sleep Apnea Detection"
Sandeep Gutta,[1] Qi Cheng,[1] Hoa Nguyen,[2] Bruce Benjamin[1]
[1]Oklahoma State University, Stillwater, USA; [2]Posts and Telecommunications Institute of Technology, Vietnam

FIRST RUNNER-UP

"A Structured Mean Field Approach for Existence-Based Multiple Target Tracking"
Roslyn A. Lau, Jason L. Williams
Defence Science and Technology Group, Australia

SECOND RUNNER-UP

"Real-Time Forecasting of an Epidemic Outbreak: Ebola 2014/2015 Case Study"
Branko Ristic,[1] Peter Dawson[2]
[1]RMIT University, Melbourne, Australia; [2]DST Group, Australia

TAMMY BLAIR BEST STUDENT PAPER AWARDS

"Approaches for Solving *m*-Best 3-Dimensional Dynamic Scheduling Problems for Large *m*"
Lingyi Zhang,[1] David Sidoti,[1] Krishna R. Pattipati,[1] David Castañón[2]

[1]University of Connecticut, Storrs, USA; [2]Boston University, Massachusetts, USA

FIRST RUNNER-UP

"Sigma-Point Filtering for Nonlinear Systems with Non-Additive Heavy-Tailed Noise"
Filip Tronarp, Roland Hostettler, Simo Särkkä
Aalto University, Finland

SECOND RUNNER-UP

"Gyro-Aided Visual Tracking Using Iterative Earth Mover's Distance"
Gang Yao, Mike Williams, Ashwin Dani
University of Connecticut, Storrs, USA

2015

JEAN PIERRE LE CADRE BEST PAPER AWARDS

"An Application of Interacting Multiple Model Tracking Method to Financial Modeling and Asset Allocation"
Shozo Mori,[1] Kuochu Chang,[2] Hajime Takahashi,[3] Chee-Yee Chong[4]
[1]Systems & Technology Research, USA; [2]Geoge Mason University, Fairfax, Virginia, USA; [3]Tottori University, Japan; [4]Indenpendent Consultant, USA

FIRST RUNNER-UP

"An Efficient Algorithm for Aircraft Conflict Detection and Resolution Using List Viterbi Algorithm"
Vesselin P. Jilkov, X. Rong Li, Jeffrey H. Ledet
University of New Orleans, Louisiana, USA

SECOND RUNNER-UP

"Trust Revision for Conflicting Sources"
Audun Jøsang,[1] Magdalena Ivanovska,[1] Tim Muller[2]
[1]University of Oslo, Norway; [2]Nanyang Technological University, Singapore

TAMMY BLAIR BEST STUDENT PAPER AWARDS

"Improvements in the Implementation of Log-Homotopy Based Particle Flow Filters"
Muhammad Altamash Khan, Martin Ulmke
FKIE Fraunhofer, Germany

FIRST RUNNER-UP

"Secure and Resilient Distributed Machine Learning under Adversarial Environments"
Rui Zhang, Quanyan Zhu
New York University, USA

SECOND RUNNER-UP

"Crowdsourcing with Multi-Dimensional Trust"
Xiangyang Liu,[1] He He,[2] John S. Baras[3]
University of Maryland, College Park, USA

2014

BEST PAPER AWARDS

"Deterministic Approximation of Circular Densities with Symmetric Dirac Mixtures Based on Two Circular Moments"
Gerhard Kurz, Igor Gilitschenski, Uwe Hanebeck
Karlsruhe Institute of Technology, Germany

FIRST RUNNER-UP

"Interacting Multiple Model Unscented Gauss-Helmert Filter for Bearings-Only Tracking with State-Dependent Propagation Delay"
Rong Yang,[1] Yaakov Bar-Shalom,[2] Jack Hong'an Huang,[1] Gee Wah Ng[1]
[1]DSO National Laboratories, Singapore; [2]University of Connecticut, Storrs, USA

SECOND RUNNER-UP

"Improved Estimation of Conflict Probability for Aircraft Collision Avoidance"
Vesselin Jilkov, X. Rong Li, Jeffrey Ledet
University of New Orleans, Louisiana, USA

BEST STUDENT PAPER AWARDS

"Multi-Object Tracking Using Labeled Multi-Bernoulli Random Finite Sets"
Stephan Reuter,[1] Ba-Tuong Vo,[2] Ba-Ngu Vo,[2] Klaus Dietmayer[1]
[1]Ulm University, Germany; [2]Curtin University, Bentley, Australia

FIRST RUNNER-UP

"A New Probability Distribution for Simultaneous Representation of Uncertain Position and Orientation"
Igor Gilitschenski,[1] Gerhard Kurz,[1] Uwe Hanebeck,[2] Simon J. Julier[1]
[1]Karlsruhe Institute of Technology, Germany; [2]University College London, United Kingdom

SECOND RUNNER-UP

"Sensor Control for Multi-Object Tracking Using Labeled Multi-Bernoulli Filter"
Amirali K. Gostar, Reza Hoseinnezhad, Alireza Bab-Hadiashar
RMIT University, Melbourne, Australia

2013

BEST PAPER AWARDS

"Recursive Fusion of Noisy Depth and Position Measurements for Surface Reconstruction"
Gerhard Kurz, Uwe Hanebeck
Karlsruhe Institute of Technology, Germany

FIRST RUNNER-UP

"Traffic Knowledge Discovery from AIS Data"
Giuliana Pallotta, Michele Vespe, Karna Bryan
NATO Centre for Maritime Research and Experimentation, La Spezia, Italy

SECOND RUNNER-UP

"A New Approach for Doppler-Only Target Tracking"
Giorgio Battistelli,[1] Luigi Chisci,[1] Claudio Fantacci,[1] Alfonso Farina,[2] Antonio Graziano[2]
[1]DINFO, Università di Firenze, Florence, Italy; [2]Selex ES, Rome, Italy

BEST STUDENT PAPER AWARDS

"Distributed Emitter Tracking Using Random Exchange Diffusion Particle Filters"
Stiven S. Dias,[1] Marcelo G. S. Bruno[2]
[1]Embraer Defense & Security, Brazil; [2]InstitutoTecnológico de Aeronáutica Divisão de Engenharia Eletrônica, Brazil

FIRST RUNNER-UP

"Recursive Estimation of Orientation Based on the Bingham Distribution"
Gerhard Kurz,[1] Igor Gilitschenski,[1] Simon Julier,[2] Uwe D. Hanebeck[1]
[1]Karlsruhe Institute of Technology, Germany; [2]University College London, United Kingdom

SECOND RUNNER-UP

"High Level Information Fusion through a Fuzzy Extension to Multi-Entity Bayesian Networks in Vehicular Ad-Hoc Networks"
Keyvan Golestan, Fakhri Karray, Mohamed S. Kamel
University of Waterloo, Canada

2012

BEST REGULAR PAPER AWARDS

"On Conservative Fusion of Information with Unknown Non-Gaussian Dependence"
Tim Bailey,[1] Simon Julier,[2] Gabriel Agamennon[1]
[1]University of Sydney, Australia; [2]University College London, United Kingdom

"Modeling Extreme Events in Spatial Domain by Copula Graphical Models"
Hang Yu,[1] ZhengChoo,[1] Wayne Isaac Uy,[1] Justin Dauwels,[1] Philip Jonathan[2]
[1]Nanyang Technological University, Singapore; [2]Shell Technology Centre, United Kingdom

"Measure of Nonlinearity for Stochastic Systems"
X. Rong Li
University of New Orleans, Louisiana, USA

BEST STUDENT PAPER AWARDS

"Particle Filter Divergence Monitoring with Application to Terrain Navigation"
Achille Murangira,[1] Christian Musso,[1] Igor Nikiforov[2]
[1]Onera, France; [2]Université Technologique de Troyes, France

"On the Reduction of Gaussian Inverse Wishart Mixtures"
Karl Granstrom,[1] Umut Orguner[2]
[1]Linkoping University, Sweden; [2]Middle East Technical University, Ankara, Turkey

"An Efficient Particle Filter for Multi-Target Tracking Using an Independence Assumption"
Wei Yi,[1] Mark Morelande,[2] Lingjiang Kong,[1] Jianyu Yang[1]
[1]University of Electronic Science and Technology of China, China; [2]University of Melbourne, Australia

2011

BEST STUDENT PAPER AWARD

"Shape Tracking of Extended Objects and Group Targets with Star-Convex RHMs"
Marcus Baum, Uwe D. Hanebeck
Kalsruhe Institute of Technology, Germany

BEST PAPER AWARD

"Histogram PMHT with Particles"
Sam Davey
Defence Science and Technology Organisation, Australia School of Electrical and Electronic Engineering; The University of Adelaide, Australia

2010

BEST PAPER AWARDS

"Shooting Two Birds with Two Bullets: How to Find Minimum Mean OSPA Estimates"
Marco Guerriero,[1] Lennart Svensson,[2] Daniel Svensson,[2] Peter Willett[3]
[1]Elettronica S.p.A, Italy; [2]Chalmers University of Technology, Gothenburg, Sweden; [3]University of Connecticut, Storrs, USA

RUNNERS-UP IN BEST PAPER

"Asynchronous Distributed Particle Filter via Decentralized Evaluation of Gaussian Products"
Boris N. Oreshkin, Mark J. Coates
McGill University, Montreal, Quebec, Canada

"Improved SMC Implementation of the PHD Filter"
Branko Ristic,[1] Daniel Clark,[2] Ba-Ngu Vo[3]
[1]DSTO, Australia; [2]Heriot-Watt University, Edinburgh, United Kingdom; [3]The University of Western Australia, Crawley

BEST STUDENT PAPER AWARDS

"Closed-Form Performance for Location Estimation Based on Quantized Data in Sensor Networks"
Yujiao Zheng, Ruixin Niu, Pramod K. Varshney
Syracuse University, New York, USA

RUNNERS-UP

"Selecting Classifiers by F-Score for Real-time Video Tracking"
Ingrid Visentini, Lauro Snidaro, Gian Luca Foresti
University of Udine, Italy

"Joint PDF Construction for Sensor Fusion and Distributed Detection"
Steven Kay,[1] Quan Ding,[1] Darren Emge[2]
[1]University of Rhode Island, Kingston, USA; [2]Edgewood Chemical Biological Center, USA

2009

BEST PAPER AWARDS

"Distributed Compression and Fusion of Nonnegative Sparse Signals for Multiple-View Object Recognition"
Allen Y. Yang, Subhransu Maji, Kirak Hong, Posu Yan, S. Shankar Sastry
University of California, Berkeley, USA

FIRST RUNNER-UP

"Evaluating the Bayesian Cramér-Rao Bound for Multiple Model Filtering"
Lennart Svensson
Chalmers University of Technology, Göteborg, Sweden

SECOND RUNNER-UP

"Tracking of Multiple Contaminant Clouds"
Francois Septier, Avishy Carmi, Simon Godsill
Cambridge University, United Kingdom

BEST STUDENT PAPER AWARDS

"Multitarget Tracking via Joint PHD Filtering and Multiscan Association"
Francesco Papi,[1] Giorgio Battistelli,[1] Luigi Chisci,[1] Stefano Morrocchi,[1] Alfonso Farina,[2] Antonio Graziano[2]
[1]Università di Firenze, Italy; [2]SELEX, Rome, Italy

FIRST RUNNER-UP

"Distributed Estimation with Data Association: Is the Nearest Neighbor the Most Informative?"
Paolo Braca,[1] Marco Guerriero,[2] Stefano Marano,[1] Vincenzo Matta,[1] Peter Willett[2]
[1]University of Salerno, Italy; [2]University of Connecticut, Storrs, USA

SECOND RUNNER-UP

"Feature-Aided Localization of Ground Vehicles Using Passive Acoustic Sensor Arrays"
Vishal Cholapadi Ravindra,[1] Yaakov Bar-Shalom,[1] Thyagaraju Damarlay[2]
[1]University of Connecticut, Storrs, USA; [2]U.S. Army Research Laboratory, Adelphi, Maryland, USA

2008

BEST PAPER AWARD

"Optimal Stationary Binary Quantizer for Decentralized Quickest Change Detection in Hidden Markov Models"
Cheng-Der Fuh,[1] Yajun Mei[2]
[1]National Central University and Institute of Statistical Science Academia Sinica, Taiwan; [2]Georgia Institute of Technology, USA

BEST STUDENT PAPER AWARD

"Improving Maritime Anomaly Detection and Situation Awareness through Interactive Visualization"
Maria Riveiro, Göran Falkman, TomZiemke
University of Skövde, Sweden

2007

BEST PAPER AWARD

"Gaussian Mixture Cardinalized PHD Filter for Ground Moving Target Tracking"
Martin Ulmke,[1] Ozgur Erdinc,[2] Peter Willett[2]
[1]FGAN–FKIE, Germany; [2]University of Connecticut, Storrs, USA

BEST STUDENT PAPER AWARD

"Fusion of One-Class Classifiers in the Belief Function Framework"
Astride Aregui,[1,2] Thierry Denoeux[2]
[1]Suez Environnement–CIRSEE, France; [2]Université de Technologie de Compiègne Cedex, France

2006

BEST PAPER AWARD

"Road Map Extraction Using GMTI Tracking"
Martin Ulmke, Wolfgang Koch
FGAN–FKIE, Germany
"A Track Before Detect Approach for Extended Objects"
Yvo Boers, Johannes N. Driessen
Thales, The Netherlands

BEST STUDENT PAPER AWARD

"Closed Form PHD Filtering for Linear Jump, Markov Models"
Muhammad Adeel Pasha,[1] Ba-Ngu Vo,[2] Hoang Duong Tuan,[1] Wing-Kin Ma[3]

[1]New South Wales University, Sydney, Australia; [2]Melbourne University, Australia; [3]National Tsing Hua University, Taiwan

2005

BEST PAPER AWARD

"A Performance Bound for Maneuvering Target Tracking Using Best-Fitting Gaussian Distributions"
Marcel Hernandez,[1] Branko Ristic,[2] Alfonso Farina[3]
[1]QintiQ Ltd., United Kingdom; [2]DSTO, Australia; [3]Alenia Marconi Systems, Italy

BEST STUDENT PAPER AWARD

"Distributed Data Association for Multi-Target Tracking in Sensor Networks"
Lei Chen, Mujdat Cetin, Alan Willsky
Massachusetts Institute of Technology, Cambridge, USA

2004

BEST PAPER AWARDS

"Decision Fusion in a Wireless Sensor Network with a Large Number of Sensors"
Ruixin Niu,[1] Pramod K. Varshney,[1] Michael Moore,[2] Dale Klamer[2]
[1]Syracuse University, New York, USA, [2]AlphaTech, USA

"Revisions and Extensions to the JDL Data Fusion Model II"
James Llinas,[1] Christopher Bowman,[2] Galina Rogova,[3] Alan Steinberg,[4] Ed Waltz,[5] Frank White[6]
[1]State University at Buffalo, New York, USA; [2]Consultant, Data Fusion & Neural Networks, USA; [3]Encompass Consulting, USA; [4]Utah State University Space Dynamics Lab, USA; [5]Advanced Information Systems, USA; [6]U.S. Navy SPAWAR Systems Center, USA

"Kalman Filter and Joint Tracking and Classification in the TBM Framework"
Philippe Smets,[1] Branko Ristic[2]
[1]Université libre de Bruxelles, Belgium; [2]DSTO, Australia

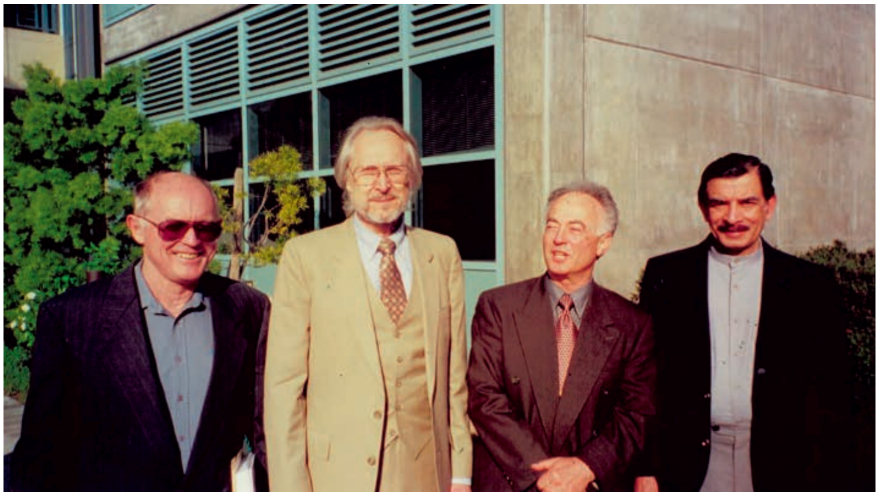
OLIVER DRUMMOND, 1928–2016

Oliver Drummond.

Oliver Drummond was a dear friend and colleague to all in the tracking and data fusion community. He had a long career of outstanding accomplishments in industry and in the development of theoretical methods. He received a Ph.D. from University of California in Los Angeles and went on to have a long distinguished career in industry, where he worked for The Aerospace Corporation, Hughes Aircraft Company, and General Dynamics. He later became a valued consultant for numerous government agencies.

His papers and lectures helped us to better understand basic concepts and to develop practical solutions to difficult problems. He published over 50 papers and lectured throughout the world and the United States. His tireless efforts as chairman of the SPIE Conference on Signal and Data Processing of Small Targets from 1989 through 2015 provided a great service, as it brought together researchers and practitioners from all over the world to exchange ideas and methods. He was well known for his humor and insight.

Oliver's sense of humor really blossomed in conference sessions when a few of his peers were present. Developing a technology does involve friendly discussions, and he was right at home in that environment. Many useful discussions went on even with the humorous portions. He was both humble in his comments to presenters and generous with his compliments. Many people attended the conference sessions to learn, but many wanted to hear his take on a particular algorithm or concept.



Left to right: Samuel S. Blackman, Oliver Drummond, Yaakov Bar-Shalom, and Rabinder N. Madan.

Oliver left a legacy that included the conference that he chaired for 27 years, the technology that he developed and wrote about, and the insight that he provided to help us to develop better solutions to practical problems. He will be sorely missed, but his work will live on.

Sam Blackman

DAVID LEE HALL, 1946–2015

David Lee Hall.

Dave completed his undergraduate studies at the University of Iowa in just three years, with a dual major in physics and mathematics. He completed the M.S. degree in astronomy from Penn State University (PSU). During a time when many of his classmates were seeking education deferments, Dave interrupted his graduate studies to serve his country, spending four years in the U.S. Air Force during the height of the Vietnam War.

Dave earned a Ph.D. degree in astronomy from PSU. Beginning in 1976 and for some 25 years thereafter, Dr. Hall supported the research, development, and application of data fusion processes and products across the scientific community and industry. This time

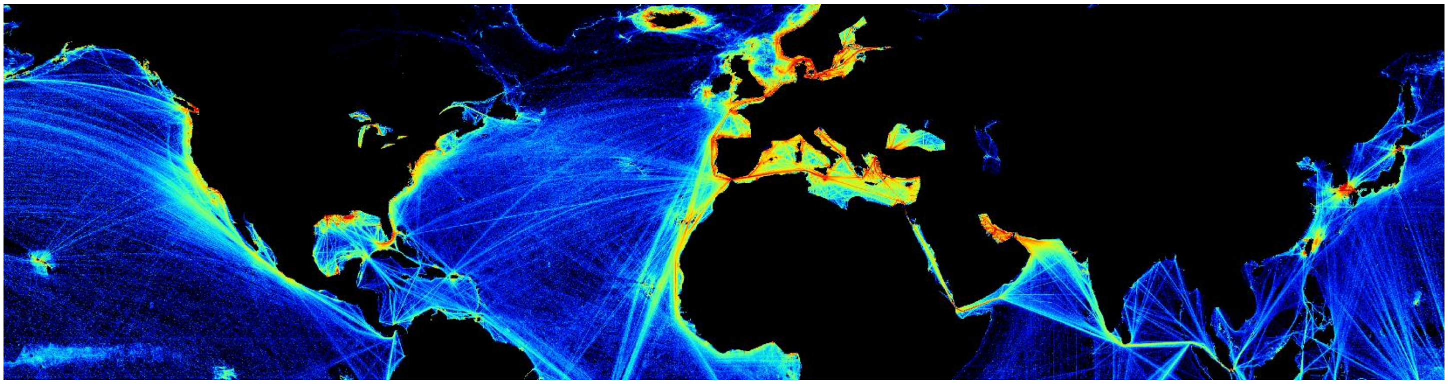
Members of the U.S. JDL Data Fusion Group 2005 (left to right: Ed Waltz, Chee-Yee Chong, Franklin White, Otto Kessler, David Hall, James Llinas, and Alan Steinberg).

included stints at MIT Lincoln Labs, Computer Sciences Corporation, and HRB Systems. Dave returned to PSU in 1993 as the Associate Director of the PSU Applied Research Laboratory (ARL). In the same year, he founded Tech Reach, Inc. At ARL, Dave provided technical leadership and strategic direction to some 150 scientists and engineers, conducting research in signal processing, intelligent sensors, information science and technology, automated reasoning, and the control of complex systems.

In 2001, Dave answered another calling: this time, joining the ranks of a nascent PSU College of Information Sciences and Technology (IST). As the founding Associate Dean for Research and Graduate Studies, he was instrumental in the establishment of the IST Research Office. Dr. Hall was tenured in 2007 as a Professor of Information Sciences and Technology. In 2007, Dave stepped down from his associate dean position to establish a new research center from which to research, promote, and teach data fusion. Hence, the Center for Network Centric Cognition and Information Fusion was born. In January 2010, Dave assumed the mantel as the third Dean of the College of Information Sciences and Technology, and IST raised $23 million toward the Penn State for the Future Campaign, achieving 130% of its campaign goal.

Dave Hall was a stalwart of the data fusion community for over 30 years. He pioneered the development of concepts and techniques that are human centric in terms of targets, information sources, and exploitation. He lectured internationally on the topics of multisensor data fusion (MSDF), artificial intelligence, research management, and technology forecasting. He was the author of over 200 technical papers, reports, book chapters, and books, including the *Mathematical Techniques in Multisensor Data Fusion* and coeditor of the *Handbook for Multisensor Data Fusion*. As a founding member of the Joint Directors of Laboratories (JDL) Data Fusion Group, his contributions were instrumental to the development of the JDL data fusion model, which remains the most widely used method for categorizing data fusion–related functions. Dr. Hall was presented the Joseph Mignogna Award in 2001 to honor his contributions as a national leader in the Data Fusion Community, and in 2003, he was named as an IEEE Fellow for his research contributions in MSDF.

James Llinas, Alan Steinberg, and Jake Graham



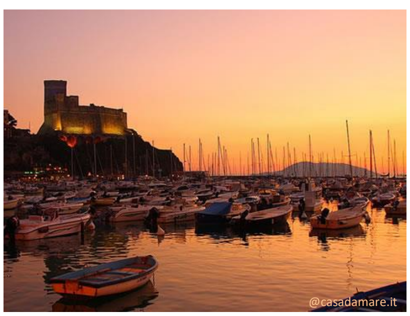
1st Maritime Situational Awareness Workshop

MSAW 2019

Science and technology meet operational needs

Villa Marigola, Lerici (SP), Italy
8-10 October 2019

The oceans connect nations globally through an interdependent network of economic, financial, social and political relationships. 70% of the Earth is covered in water; 80% of the world's population lives within 100 miles of the coast; 90% of the world's commerce is seaborne and 75% of that trade passes through a few vulnerable canals and international straits. The maritime environment includes trade routes, choke points, ports, and other infrastructure such as pipelines, oil and natural gas platforms, and trans-oceanic telecommunications cables. **– NATO Alliance Maritime Strategy (AMS) [2011]**



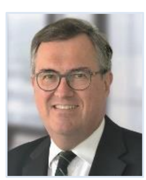
The NATO Science and Technology Organization Centre for Maritime Research and Experimentation (STO-CMRE), with the support of the EU Horizon 2020 programme, is organizing a workshop to present and discuss advanced technologies, innovative concepts, and emerging scientific challenges with respect to current and future Maritime Situational Awareness (MSA) operational needs.

With the theme "*Science and technology meet operational needs*," MSAW 2019 foresees productive collaboration and synergistic discussion among operational experts and scientists from national governments, military, academia and industry to discuss their respective challenges regarding MSA. The objective of MSAW 2019 is to foster the cross-fertilization of ideas from scientific and military domains, toward the design and implementation of future solutions tailored to MSA operational needs.

Keynote Speakers

Prof. James Llinas
Director Emeritus, Center for Multisource Information Fusion
University at Buffalo

Reexamining Information Fusion-Sensemaking-Decision Making Interdependencies — Again



Prof. Dr. Wolfgang Koch
Head of Dept. Sensor Data and Information Fusion
Fraunhofer FKIE

Artificial Intelligence for Maritime Multisensor Situation Pictures

Dr. Alfonso Farina
Life Fellow IEEE
Selex-ES (retired)

Maritime Surveillance: Radar Technologies and Scenario Characteristics

Registration is free and closes on 8 September 2019
Please see details for registration at www.cmre.nato.int/msaw

For further information, please visit MSAW 2019 website at

www.cmre.nato.int/msaw

msaw@cmre.nato.int

ISIF VISION STATEMENT

The International Society of Information Fusion (ISIF) is the premier professional society and global information resource for multidisciplinary approaches for theoretical and applied INFORMATION FUSION technologies. Technical areas of interest include target tracking, detection theory, applications for information fusion methods, image fusion, fusion systems architectures and management issues, classification, learning, data mining, Bayesian and reasoning methods.

ISIF Journal of Advances in Information Fusion (JAIF)

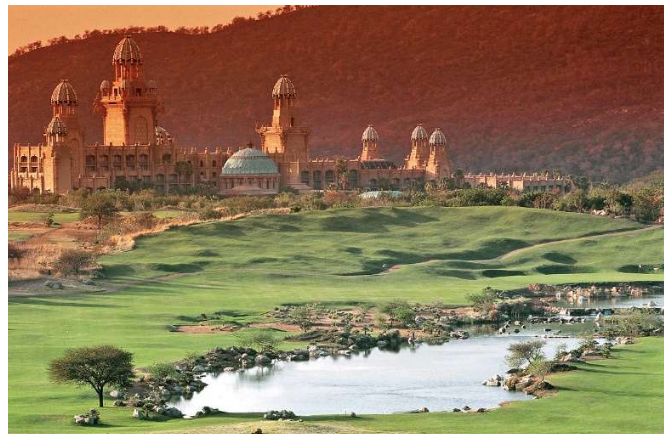
The Journal of Advances in Information Fusion (JAIF) is the flagship journal of ISIF. JAIF is an open-access, peer-reviewed, semi-annual, archival journal published electronically and distributed via the internet. JAIF was founded in July 2006. The journal is indexed at SCOPUS, free for authors, and freely available for readers at http://www.isif.org/journals/all. Authors are invited to submit both regular papers as well as short correspondences describing advances, applications, and new ideas in information fusion, both theory and application. Authors of papers presented at our annual International Conference on Information Fusion are strongly encouraged to consider submitting expanded versions of their papers to JAIF. Manuscripts can be submitted at http://jaif.msubmit.net.

Perspectives

Sun City Convention Centre
North West Province
South Africa, 6-9 July 2020
http://www.fusion2020.org

FUSION | 2020

VENUE



The 23rd International Conference on Information Fusion will take place at the Sun City Convention Centre, Rustenburg, South Africa. The venue is accustomed to hosting large international events, and being 200km from Johannesburg, it offers easy access via car rental, regular shuttle services and flights to a nearby airport.

PROGRAMME

The conference will take place from 6 to 9 July 2020 and offers the following programme:

- Monday 6 July: Tutorials and conference registration
- Tuesday 7 July: Conference and safari game drive followed by sundowner cocktails
- Wednesday 8 July: Conference and banquet
- Thursday 9 July: Conference and close

The International Conference on Information Fusion is the premier forum for interchange of the latest research in data and information fusion, and its impacts on our society. The conference brings together researchers and practitioners from academia and industry to report on the latest scientific and technical advances. Topics of interest include information fusion theory and representation, algorithms for target tracking, target and sensor modelling and evaluation and applications of information fusion such as IoT, robotics, big data, AI, autonomous systems *etc*.

SOCIAL PROGRAMME

The social programme will include a 3 hour safari game drive on 6 July in the neighbouring Pilanesberg National Park, including a halfway stop to serve sundowner drinks and snacks while listening to sounds of the African bush. Attendees will then proceed to the Botsalanong Boma, a unique open-air African banqueting venue, which with a huge bonfire and African dancers will make it an unforgettable experience under the stars for all. A banquet will take place on the evening of 7 July in the King's Ballroom, where attendees will experience true African abundance!

ACCOMMODATION

Sun City offers four individual on-site hotels. The exclusive Palace of the Lost City is ideal for those looking for a truly luxurious 5-star getaway. The Cascades is an upmarket luxury hotel set in beautiful gardens featuring pools and waterfalls. The Soho was the very first hotel established and offers a modern look and feel. The Cabanas is the ideal affordable accommodation to suit active families and budget travellers. The nearby Kingdom Resort offers neat and affordable accommodation with regular shuttles to Sun City that will be made available for the conference.