ISIF

Perspectives On Information Fusion

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25 YEARS OF FUSION CONFERENCES: COLLECTION OF MEMORIES

ON THE DEFINITION AND SCOPE OF INFORMATION FUSION AS A FIELD OF RESEARCH

QUANTUM ALGORITHMS FOR DATA FUSION: TRENDS AND APPLICATIONS

AGENTS WITH FREE WILL: A THEORY GROUNDED IN QUANTUM PHYSICS

Publication of the
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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 significant original research should be directed to the ***Journal of Advances in Information Fusion*** (JAIF) or another research journal. The standing Call for Papers (CfP) for ***Perspectives*** is posted at https://isif.org/.

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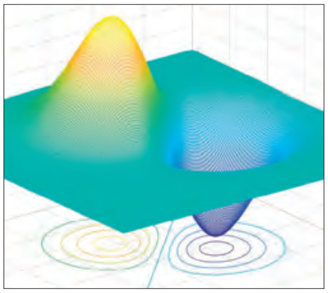

PERSPECTIVES MAGAZINE

Welcome to the fifth issue of *Perspectives* magazine! I hope you are comfortably installed in a quiet place at the 25th FUSION conference in Linköping, in Sweden. Let me first welcome two new members to the *Perspectives* Editorial team: Paulo Costa accepted the role of Associate Editor (AE) for the area of Higher Level Information Fusion, and Kristy Virostek of Conference Catalysts is back in her role of Production Manager (PM) that she could not afford last year. It is a real pleasure to have them on board.

After two years of pandemic, the FUSION conference is back to a full physical format in Europe, for the second time in Sweden, after the 2004 edition in Stockholm. This fifth issue of *Perspectives* is thus an opportunity to look back and look forward.

Looking back, the Information Fusion History department reviews the long path of construction of the Fusion community, through the lens of its flagship events that have been held yearly on the five continents at the International Conference of Information Fusion. In a seminal paper, chairs of the 24 conferences since 1998 dig into their memories to tell their stories about the event's organization, with concluding remarks from the FUSION 2022 general cochairs. I am extremely grateful for their generosity in sharing the invaluable fond memories that explain the genesis of the Fusion community. I would like to thank them for taking time to write these words and find photos (special thank you to Jean Dezert), where smiles give life to stories and allow us to remember those who left us. Let me finally thank Chee-Yee Chong, one of the few attendees of every conference, for providing the introduction of this paper, as well as precious advice and precise memories.

Still looking back, the first feature paper is provided by a Swedish team of authors from the Swedish Defence Research Agency (FOI), the University of Skövde (HIS), the Integrated Transport Research Lab (ITRL/KTH), and Linköping University. In their paper "On the Definition and Scope of Information Fusion as a Field of Research", the authors Ronnie Johansson, Alexander Karlsson, Sten F. Andler, Marcus Brohede, Maria Klingegård, Joeri van Laere, and Tom Ziemke walk us through the different definitions of Information Fusion, and pave the way to future research on connected topics.

Looking back is necessary to build the future. Formalization from quantum theory has proven in the last years to be useful in many fields and Information Fusion makes no exception, as reflected in this issue of *Perspectives*. Wolfgang Koch in his paper "Quantum Algorithms for Data Fusion: Trends and Applications" presents some ongoing work within his team at Fraunhofer FKIE, highlighting the potential of quantum algorithms for solving tracking problems, with perspectives for resources management. Kathryn Blackmond Laskey from George Mason University (GMU) analyzes herself how quantum models can support a theory of free will for agents, in her paper, "Agents with Free Will: A Theory Grounded in Quantum Physics".

The issue also includes a report on the 2021 FUSION conference, the first held on the African continent. After a (forced) virtual event in 2020, the general cochairs Pieter de Villiers (University of Pretoria), Alta de Waal (University of Pretoria), and Fredrik Gustafsson (Linköping University) hosted attendees at the Sun City facilities in South Africa, offering them the unique chance of seeing the "big five" animals. The FUSION 2021 Best Paper and Best Student Paper awards are presented by the conference award chair Nageswara Rao (Oak Ridge National Laboratories). The International Society of Information Fusion (ISIF) award program chaired by W. Dale Blair recognizes Edward Waltz for the Yaakov Bar-Shalom Award for a Lifetime of Excellence in Information Fusion and Florian Meyer for the Young Investigator Award.

You will also have the pleasure to read a detailed and stimulating review by Jesus Garcia Herrero (Universidad Carlos III de Madrid) of a sample of chapters from the book *Systems Engineering and Artificial Intelligence* edited by William F. Lawless, Ranjeev Mittu, Donald A. Sofge, Thomas Shortell, and Thomas A. McDermott. A short report on the ISIF working group by Darin Dunham (Lockheed Martin) and a brief on the interesting project "Automation in UAV Remote Deliveries" by Nickolay Jelev (Windracers), James Scanlan (Southampton University), and Charles Scales (Windracers) complete the issue. As usual, advertisements for future events will hopefully stimulate your next conference participation.

This fifth issue of *Perspectives* would clearly not exist without the contributions of all authors, the careful reviews of the Associate Editors Wolfgang Koch, Lyudmila Mihaylova, Murat Efe, Emre Ozkan, Jesus Garcia Herrero, Paulo Costa, the invaluable and insightful advice of the AEiC Roy Streit, and the support of the Administrative Editor, David W. Krout. Thank you to all for your dedication, ideas, and energy.

Anne-Laure Jousselme
Editor-in-Chief
Perspectives on Information Fusion

On the Definition and Scope of Information Fusion as a Field of Research

***Abstract*—**A definition of information fusion (IF) as a field of research can benefit researchers within the field, who may use such a definition when motivating their own work and evaluating the contributions of others. Moreover, it can enable researchers and practitioners outside the field to more easily relate their own work to the field and more easily understand the scope of IF techniques and methods. Based on strengths and weaknesses of existing definitions, a definition is proposed that is argued to effectively fulfill the requirements that can be put on a definition of IF as a field of research. Although the proposed definition aims to be precise, it does not fully capture the richness and versatility of the IF field. To address that limitation, we highlight some topics to explore the scope of IF, covering the systems perspective of IF and its relation to machine learning, optimization, robot behavior, opinion aggregation, and databases.

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INTRODUCTION

In 2007, some 10 years after the inception of the International Society of Information Fusion (ISIF) information fusion (IF) conference, we set out to review the multitude of definitions for the subject that had been proposed until then and to craft a unifying definition. Our work was eventually presented in a technical report [1]. Over the years, other authors have cited the report repeatedly. The persistent interest in the report has prompted us to revisit the topic, now almost 15 years later; incorporate aspects of IF not explicitly covered by the proposed definition; and publish the work properly in this journal for future reference. Although we add a few definitions to our list, our proposed definition remains unchanged. Instead, we briefly explore some related topics that might be useful in a holistic perspective on IF systems.

Our aspiration is that the current paper will remain an attractive source of historical perspective on the emergence of the IF field, as well as an outlook on the scope of the field, to newcomers and seasoned practitioners alike.

The word "fusion"[1] is (colloquially and professionally) used in several contexts, perhaps predominantly in nuclear physics and enterprise mergers. By IF, we loosely mean, in a general and inclusive sense, exploitation of clues (e.g., signals, observations, evidence, and opinions) from (information) sources in the context of information processing to a decision-relevant state of interest. Therefore, a discussion of the interrelation and mutual dependencies of the concepts of IF, data fusion, and sensor fusion is an inhibitive distraction and outside the scope of this paper.

Also beyond this paper's scope is establishing differences in properties of source output, such as data, information, knowledge, evidence, and opinions. Furthermore, many different specialized subdomains have been defined, including image, feature, decision, and behavior fusion. In this study, we consider all of them to contribute to the characteristics of the IF field.

Although the proposed definition aims to restrict the limits of the field of IF, we simultaneously acknowledge a need to explore its scope to learn what can be expressed within the scope of IF and what concepts, solutions, and tools can be adopted from interacting technological and research fields (such as optimization and robotics). A potential benefit from such an endeavor is the invention of novel hybrid algorithms and more competent fusion systems.

The IF field builds on many different results that all can be applied to fuse data, including historical results from 18th- and 19th-century scholars such as Carl-Friedrich Gauss (mathematical statistics), Thomas Bayes (subjective probability and inference), and Nicolas de Condorcet (jury theorem [2]), current advances in machine learning [3], and the future potential of quantum computing [4].

The potential benefits of IF are quite domain agnostic, and hence unsurprisingly, applications exist in multiple domains, e.g., biometrics [5]; computer vision and image processing [6]; data mining [7]; machine learning [8], [9], [10]; information retrieval [10]; remote sensing [11]; robotics [12]; target tracking [13]; vehicle control [14]; and wireless sensor networks [15].

Three strategies for exploiting multiple sources have been presented [16]: complementary (sources providing separate, noninteracting data, such as surveillance cameras with nonoverlapping views); competitive (sources reporting on the same entity and providing redundant information that can be exploited to reduce uncertainty); and cooperative (sources providing

[1] Synonyms or related keywords encountered in the literature that also express the process of fusion: aggregate, amalgamate, blend, combine, integrate, merge, pool, and synthesize.

information that can be used to derive information not inferable by either source alone).[2] Hybrids of two or more of these strategies are possible [17].

A precise definition of IF as a field of research may be important for practitioners whose interest in applying techniques developed in the field may increase with a better understanding of the types of problems addressed by these techniques. Furthermore, such a definition would allow researchers outside the area to more easily relate their own research to the field of IF and thereby allow a higher degree of cross-fertilization among different fields. Equally important to being able to conclude that something is a contribution to the field is being able to determine what is not a contribution—a too-loose definition would allow the inclusion of only vaguely related topics with minor relevance to the field as a whole. Hence, such a definition could also clearly play an important role for researchers already inside the field who have to motivate the relevance of their own work, as well as evaluate the contributions of others to the area.

However, such a definition only partially helps with exploring the scope of IF. To complement it, we continue to discuss some topics that relate to IF and seem to provide further insight regarding the content of its scope.

In the next section, we include a discussion (largely unaltered) of previous definitions of IF from our report [1]. Based on the limitations of these definitions, when it comes to defining the field of research, we suggest a novel definition that is more inclusive in some respects compared with several earlier definitions but can be used to more clearly conclude what is not considered a contribution to the field of research.

Although the proposed definition aims to be compact, we go on to highlight results that help to explore parts of the full scope of IF. We end with a discussion of the proposed definition. The full list of surveyed IF definitions is included in the appendix.

A PROPOSED DEFINITION OF THE RESEARCH FIELD

The basis for the following discussion is the definitions[3] of IF included in the appendix.[4]

DEFINITION CRITERIA

In the ideal case, several criteria should fulfill a definition of a research field. We consider the following three general criteria:

- Discipline, i.e., is it clear what the scientific fundaments of the research field are?
- Goal, i.e., does the definition clearly state what the goal of the research is, and is it obvious what can be considered progress toward this goal?
- Contribution, i.e., is it clear by what means the research field approaches the goal?

[2] A fourth strategy to consider could be coordinated (i.e., loosely coupled sources), covering one source queuing the other or providing context for data interpretation.

[3] We use the term "definition" loosely at this point, because IF sometimes is not explicitly defined but rather is outlined in passing.

[4] Other discussions of IF definitions can be found in [5, p. 13] and [33, p. 70].

DISCIPLINE

With only few exceptions, none of the definitions surveyed (see the appendix) explicitly positions the field as concerning the development of artifacts (i.e., an engineering science). In principle, the IF process as described in several of the definitions could equally refer to biological systems,[5] although most of them implicitly assume artificial systems. Only one definition mentions the scientific basis of the field: "As a technology, data fusion is actually the integration and application of many traditional disciplines and new areas of engineering to achieve the fusion of data" [18].

GOAL

Among the suggested goals one can find the following:

- "To achieve refined position and identity estimates" [19]
- "To refine state estimates and predictions" [20]
- To obtain "information of greater quality" [21]
- "To infer relevant situations and events related to the observed environment" [22]
- To maximize "the useful information content, for improved reliability or discriminant capability, while minimising the quantity of data ultimately retained" [23]
- "To perform inferences that may not be possible from a single sensor alone" [24]
- "To provide a better understanding of a given scene" [25]
- "The resulting decision or action is in some sense better (qualitatively and quantitatively, in terms of accuracy, robustness, etc.)" [26]
- To obtain "information that has greater benefit than what would have been derived from each of the contributing parts" [27]

Although some of these statements indicate how to measure progress toward the goal, e.g., by estimating the accuracy of predictions and estimates or the benefit for a decision maker, this is less clear in other cases either because of a vague target (e.g., greater quality) or because it is unclear why the entity by which progress is to be measured should be optimized (e.g., what is the purpose of performing inferences?).

Several aspects considered by some definitions would further restrict the focus of the research field:

- Sources, i.e., the definition could be restricted to certain types of data or information, e.g., from sensors
- Scenario, i.e., the definition could be restricted to certain types of applications or decision situations, e.g., time-critical decision making
- Type of process, i.e., the definition could be restricted to certain characteristics of the fusion process, e.g., continuous refinement

[5] Hall and McMullen, e.g., point out [36] that the use of "fusion" is hardly innovative, because animals have always used an integration of different senses to survive.

CONTRIBUTION

Almost all definitions indicate that progress toward the goal is to be achieved by combining information from multiple sources. Some definitions try to characterize from where the benefit of combining information from multiple sources comes, as expressed in phrases such as "than would be possible, if these sources were used individually" [28] and "that has greater benefit than what would have been derived from each of the contributing parts" [27].

The problem with these definitions is that the alternative to combining information from multiple sources is unclear. One possible interpretation is that the alternative is to use only one of the sources. Hence, these definitions would state that the benefit of IF can be obtained by multiple sources rather than a single source, something that also seems to be implied by "than could be achieved by the use of single sensor alone" [29]. However, such statements are almost truisms, falsified only if the different sources provide redundant information. Another possible interpretation is that there is some straightforward way of combining the information from these sources, as opposed to the intended way that leads to a "greater benefit than the sum of the contributing parts" [30]. However, it is not clear what corresponds to this straightforward way (i.e., what constitutes "the sum of the contributing parts"); thus, the definitions provide no indication of how to measure progress. Furthermore, one could argue that the goal of the research field should be more compelling than just trying to outperform single-source solutions or straightforward ways of combining information from multiple sources.

THE PROPOSED DEFINITION

DEFINITION

"Information fusion is the study of efficient methods for automatically or semiautomatically transforming information from different sources and different points in time into a representation that provides effective support for human or automated decision making."

MOTIVATION

The definition states that the field is concerned with the synergistic transformation of information. This term is intended to cover all possible ways of combining and aggregating to infer, as well as to reduce, information. The transformation itself may require decisions supported by other transformations. We have chosen to emphasize that in addition to transforming information from different sources, we include transformation of information obtained from a single source at different points in time; e.g., a sensor often is conceived to persist over time. Sources can be of many kinds (e.g., sensors, databases, simulations, and humans). Similarly, information can be obtained from different types of data: text, numbers, graphs, etc.

The definition further stresses that the transformation is either automatic or semiautomatic, indicating that the field is restricted to artifacts, possibly acquired in cooperation with humans, and excluding purely biological systems from the scope of the definition. Hence, the field can be considered as belonging to the engineering sciences. This does not rule out that a great deal might be learned from the biological and cognitive sciences regarding how different senses are integrated in biological systems [31]. Furthermore, semiautomatic transformation could involve man-in-the-loop integration (e.g., human expert adjudicating fusion results or resolving conflicting results) or man-on-the-loop integration (e.g., human expert controlling the context of the fusion process, including altering the set of accessible dynamic models) while boosting trust for the IF system. An example of such human–machine data fusion is provided by Muesing et al. [32].

The definition points out that the transformation of information should be efficient and that it should result in effective support. This means that research contributions to this field should be evaluated based on the following:

1. Their effect on the decision-making process (human or automated) compared with alternative approaches
2. The cost of achieving that effect with respect to consumption of time and other resources compared with alternative solutions

DISCUSSION

An ideal definition should primarily provide guidance for researchers within the field on how to make progress. We believe that the proposed definition accomplishes this, since it quite clearly shows what is to be required from studies in the field.

A particular study within IF should, according to the definition, increase our understanding of what effect different methods of transforming information have on support in different decision situations and with different sources of information or how to achieve an effect in an efficient way. Such a study would then typically contribute to the field by providing new empirical evidence or theoretical arguments that certain methods of transforming information are superior to others for certain kinds of decision scenarios, evaluation criteria, and sources. Methods that support or facilitate the transformation are also relevant here, including methods for sensor management, process adaptation, data association and alignment, and infrastructure design. Studies may also contribute to the field by showing what requirements a particular decision situation puts on the methods for transforming the information.

The definition excludes work that brings no new knowledge regarding either the effectiveness or the efficiency of different ways of transforming information, since such studies will not contribute to the goal of understanding what results in the most efficient and effective support. We also believe that the proposed definition can be accepted by practitioners and researchers outside the field, since it—like most previous definitions—does not assume familiarity with field-specific terminology.

SUPPLEMENTARY PERSPECTIVES

A fair proportion of the research literature in the IF field concerns issues such as improved filtering techniques and combination rules. That part of the literature is well covered elsewhere. Here, we briefly discuss some topics that may provide the IF field with supplementary perspectives that can be useful for exploring the scope of IF and developing more comprehensive and versatile IF systems.

ALGORITHMIC AND SYSTEMS PERSPECTIVES

It is often helpful to study IF from both an algorithmic perspective and a systems perspective (SP). The former emphasizes the foundations of IF algorithms, their applicability, and their performance. The SP was entered into the widely acknowledged Joint Directors of Laboratories (JDL) model in the early 1990s [33, p. 75], covering control of the fusion process, centralized versus distributed architecture, knowledge bases, and varying mission and decision-maker objectives.

The SP encompasses multisensor integration [12], which concerns all kinds of synergistic uses of information sources, including the strategy labeled as coordination (described in the introduction). Since the SP does not require directly collaborating sources, additional quality metrics such as the system's spatial and temporal coverage, robustness to failure, decision maker's utility, and level of achieved autonomy emerge. The latter item also illuminates IF as part of the perception capabilities of an intelligent agent.

DATA MINING AND MACHINE LEARNING

Making a clear distinction between data mining and machine learning (DMML) is challenging—as is distinguishing IF from DMML, because both focus on exploiting data for improved insight and decision making. Roughly, IF can be considered to have the qualities of being online, sequential, and deductive, whereas DMML is offline, batch driven, and inductive. In practice, there are abundant exceptions, and the division is not clear-cut.

In the literature, examples (1) of DMML supporting IF, (2) of IF supporting DMML, and (3) with IF and DMML are indistinguishable. An example of option 1 was provided in 1998 by Waltz [34], in which observations were simultaneously fed to a DMML and an IF module. The former learns the parameters of dynamic models that are used by the latter for improved state estimation. Some examples of option 2 were provided by Torra [7] and Marcos and Azcarraga [35], including preprocessing data (data cleansing by reducing uncertainties) and fusing classifier output [8]. Finally, for option 3, a trained ANN can be seen as a fusion operator [36].

OPTIMIZATION PERSPECTIVE

IF can be seen as an explicit optimization problem, i.e., finding the world state that is most consistent with observed world data. By taking this approach, optimization tools may be leveraged for IF. A few examples of this interpretation exist [37] that approach the Kalman filter from an optimization perspective. IF might also benefit from using other optimization techniques, such as linear programming [38], distributed optimization [39] (e.g., fusing preprocessing opinions), and bilevel optimization [40].

ROBOTIC BEHAVIOR AND COMMAND FUSION

Research on autonomy in mobile robotics has explored the idea of fusing commands rather than information. Independent modules representing different kinds of competing robot behaviors (e.g., collision avoidance) jointly produce output action. In IF, uncertainty in information is usually treated explicitly, but in command fusion, each behavior module evaluates the current world state and proposes a preferred command; these are then fused into a final selected action. A few methods applying voting and fuzzy logic approaches for command fusion have been surveyed [41].

AGGREGATION OF OPINIONS

Far from all imaginable fusion rules are akin to Bayesian inference. Subfields concern the joint decisions of committees of "expert" agents whose aggregation[6] rules seek consensus, rather than reinforcement of Bayesian posteriors. One example is social choice theory in multiagent systems [42], which encourages an axiomatic analysis of aggregation rules. Other types of aggregation rules have been presented [43]. In wireless sensor networks, aggregation is a common topic, but it usually focuses on reduction of energy usage and data transmission [15], [44].

DATABASE INTEGRATION

The need for fusion also occurs when multiple databases or knowledge bases, with semantically overlapping content, are in use. Typically, the involved databases are immutable to the fusion process, which is performed on the fly when a query is issued. The process is called data integration and aims to provide a unified view of the collection of data sets while resolving inconsistencies, in part, using fusion methods. In [45], the authors resolve inconsistencies in relational data on three levels—schema, tuple, and value—employing various strategies to resolve inconsistent values, such as maximum value, voting, or letting the user decide.

CONCLUDING REMARKS

We have summarily reviewed a large number of definitions for sensor, data, and IF and discussed them in terms of whether they clearly state the goal for the research field, the scientific fundaments, and in what way the field is supposed to approach the goal. Based on limitations or restrictions of earlier definitions, we have presented a novel definition that clearly points out a goal for the research field, how the field approaches the goal, and implicitly that the field can be considered an engineering science. Furthermore, we have argued that the definition can be used for clearly distinguishing what should—and what should not—be considered a contribution to the field. We also believe that researchers and practitioners outside the field can relate to the definition, which allows cross-fertilization, as well as the promotion of interests, in applying tools and techniques developed in the field.

[6] In that domain, the term "aggregation" is preferred.

To obtain a more complete understanding of the implications of the definition—including the relevance of the field for other fields and areas of application—the terms in the definition require further exploration and clarification. This includes providing more exact characterizations of the following:

1. The methods used for transforming information
2. The eligible sources of information
3. The technical infrastructures to automate IF
4. The effects of IF in different decision-making situations
5. The potential decision-making situations for using IF systems

This list is by no means complete, which means that it will continue to evolve as the research field advances.

ACKNOWLEDGMENTS

The original work on IF as a research field was directed by Prof. Henrik Boström (presently at the KTH Royal Institute of Technology, Stockholm) and supported by the Information Fusion Research Program at the University of Skövde, in partnership with the Swedish Knowledge Foundation under grant 2003/0104 and participating partner companies. A language review was performed by Katherine Calvin. The current revision of the report was supported by the research and development program of the Swedish Armed Forces and the Excellence Center at Linköping-Lund in Information Technology.

APPENDIX. DEFINITIONS OF FUSION

In this appendix, we present several definitions of IF (or subdomains) put forward over the years. In many cases, the definitions are aged, possibly reflecting that the need to invent definitions was more imperative in the vibrant early days. More recently, authors seem to be largely content with referring to the old definitions. One perspective on fusion that has emerged in recent years but is not covered by these definitions is that of contextual information [46].

Only a few of the definitions covered try to define a field of research. Most of them define these terms as processes. These are nevertheless included here since they, with only a little modification, in principle could serve as definitions for the research field (e.g., "Information fusion is a research field concerned with the study of processes for…").

Definitions that have been added since our previous report [1] are marked with an asterisk. The definitions are tagged with superscript letters representing the supposed domain of origin.[7]

JDL (1987)[t]

Data fusion is "a process dealing with the association, correlation, and combination of data and information from single and multiple sources to achieve refined position and identity estimates, and complete and timely assessments of situations and threats, and their significance. The process is characterized by continuous refinements of its estimates and assessments, and the evaluation of the need for additional sources, or modification of the process itself, to achieve improved results." [19]

DURRANT-WHYTE (1988)[r]

"The basic problem in multi-sensor systems is to integrate a sequence of observations from a number of different sensors into a single best-estimate of the state of the environment." [47]

LLINAS (1988)[t]

"Fusion can be defined as a process of integrating information from multiple sources to produce the most specific and comprehensive unified data about an entity, activity or event. This definition has some key operative words: specific, comprehensive, and entity. From an information–theoretic point of view, fusion, to be effective as an information processing function, must (at least ideally) increase the specificity and comprehensiveness of the understanding we have about a battlefield entity or else there would be no purpose in performing the function." [48]

RICHARDSON AND MARSH (1988)[r]

"Data fusion is the process by which data from a multitude of sensors is used to yield an optimal estimate of a specified state vector pertaining to the observed system." [18]

MCKENDALL AND MINTZ (1988)[r]

"The problem of sensor fusion is the problem of combining multiple measurements from sensors into a single measurement of the sensed object or attribute, called the parameter." [49]

WALTZ AND LLINAS (1990)[t]

"This field of technology has been appropriately termed data fusion because the objective of its processes is to combine elements of raw data from different sources into a single set of meaningful information that is of greater benefit than the sum of the contributing parts.

As a technology, data fusion is actually the integration and application of many traditional disciplines and new areas of engineering to achieve the fusion of data." [30]

LUO AND KAY (1992)[r]

"Multisensor fusion … refers to any stage in an integration process where there is an actual combination (or fusion) of different sources of sensory information into one representational format." [12]

ABIDI AND GONZALEZ (1992)[r]

"Data fusion deals with the synergistic combination of information made available by various knowledge sources such as sensors, in order to provide a better understanding of a given scene." [25, p. xi]

[7] Symbols: d (database), i (image), r (robotics), s (remote sensing), t (target tracking), w (wireless sensor networks), or left out if generic or unknown.

HALL (1992)[t]

"Multisensor data fusion seeks to combine data from multiple sensors to perform inferences that may not be possible from a single sensor alone." [24]

DEFENCE SCIENCE AND TECHNOLOGY ORGANIZATION (1994)[t]

Data fusion is "a multilevel, multifaceted process dealing with the automatic detection, association, correlation, estimation, and combination of data and information from single and multiple sources." [50]

MALHOTRA (1995)[t]

"The process of sensor fusion involves gathering sensory data, refining and interpreting it, and making new sensor allocation decisions." [51]

ANTONY (1995)[t*]

"Data fusion is the process of combining evidence to support intelligence generation." [52]

HALL AND LLINAS (1997)[t]

"Data fusion techniques combine data from multiple sensors, and related information from associated databases, to achieve improved accuracy and more specific inferences than could be achieved by the use of single sensor alone." [29]

GOODMAN ET AL. (1997)[t]

Data fusion is to "locate and identify many unknown objects of many different types on the basis of different kinds of evidence. This evidence is collected on an ongoing basis by many possibly allocatable sensors having varying capabilities" and to "analyze the results in such a way as to supply local and over-all assessments of the significance of a scenario and to determine proper responses based on those assessments." [53]

PARADIS ET AL. (1997)[t]

"Data fusion is fundamentally a process designed to manage (i.e., organize, combine and interpret) data and information, obtained from a variety of sources, that may be required at any time by operators or commanders for decision making.… Data fusion is an adaptive information process that continuously transforms available data and information into richer information, through continuous refinement of hypotheses or inferences about real-world events, to achieve a refined (potentially optimal) kinematics and identity estimates of individual objects, and complete and timely assessments of current and potential future situations and threats (i.e., contextual reasoning), and their significance in the context of operational settings." [54]

STARR AND DESFORGES (1998)

"Data fusion is a process that combines data and knowledge from different sources with the aim of maximising the useful information content, for improved reliability or discriminant capability, while minimising the quantity of data ultimately retained." [23]

WALD (1998)[s]

"Data fusion is a formal framework in which are expressed means and tools for the alliance of data of the same scene originating from different sources. It aims at obtaining information of greater quality; the exact definition of greater quality will depend upon the application." [21]

EVANS (1998)

Data fusion is "the combining of data from different complementary sources (usually geodemographic and lifestyle or market research and lifestyle) to 'build a picture of someone's life'." [55]

WALD (1999)[s]

"Data fusion is a formal framework in which are expressed the means and tools for the alliance of data originating from different sources." [56]

STEINBERG ET AL. (1999)[t]

"Data fusion is the process of combining data to refine state estimates and predictions." [20]

GONSALVES ET AL. (2000)[t]

"The overall goal of data fusion is to combine data from multiple sources into information that has greater benefit than what would have been derived from each of the contributing parts." [27]

HANNAH ET AL. (2000)

"Fusion is defined materially as a process of blending, usually with the application of heat to melt constituents together (OED), but in data processing the more abstract form of union or blending together is meant. The 'heat' is applied with a series of algorithms which, depending on the technique used, give a more or less abstract relationship between the constituents and the finished output." [57]

HALL AND LLINAS (2001)[t]

"Information fusion is an Information Process dealing with the association, correlation, and combination of data and information from single and multiple sensors or sources to achieve refined estimates of parameters, characteristics, events, and behaviors for observed entities in an observed field of view. It is sometimes implemented as a Fully Automatic process or as a Human-Aiding process for Analysis and/or Decision Support." [58]

DASARATHY (2001)

"Information fusion encompasses the theory, techniques, and tools conceived and employed for exploiting the synergy in the information acquired from multiple sources (sensor, databases, information gathered by humans etc.) such that the resulting decision or action is in some sense better (qualitatively and quantitatively, in terms of accuracy, robustness and etc.) than would be possible, if these sources were used individually without such synergy exploitation." [26]

APPRIOU ET AL. (2001)
"Fusion consists in conjoining or merging information that stems from several sources and exploiting that conjoined or merged information in various tasks such as answering questions, making decisions, numerical estimation, etc." [59]

MCGIRR (2001)
"The process of bringing large amounts of dissimilar information together into a more comprehensive and easily manageable form is known as data fusion." [60]

LAMBERT (2001)[t*]
"Data fusion is the process of utilizing one or more data sources over time to assemble a representation of aspects of interest in an environment." [61]

DURRANT-WHYTE (2001)[r*]
"Data fusion is the process of combing information from a number of different sources to provide a robust and complete description of an environment or process of interest. Data fusion is of special significance in any application where a large amounts of data must be combined, fused and distilled to obtain information of appropriate quality and integrity on which decisions can be made." [62, p. 4]

BELL ET AL. (2002)
"Sophisticated information fusion capabilities are required in order to transform what the agents gather from a raw form to an integrated, consistent and complete form. Information fusion can occur at multiple levels of abstraction." [63]

LI ET AL. (2003)[t*]
"Estimation fusion, or data fusion for estimation, is the problem of how to best utilize useful information contained in multiple sets of data for the purpose of estimating an unknown quantity—a parameter or process (at a time). These data sets are usually obtained from multiple sources (e.g., multiple sensors)." [64]

SHARMA AND APURVA (2003)*
"The task of sensor data fusion involves integration of numerous data streams, originating from separate sensors, into a consistent model that represents the pertinent high-level features of the tactical environment and then to present an assessment of their significance." [65]

CHALLA ET AL. (2005)[w]
Multisensor data fusion "is a core component of all networked sensing systems, which is used either to:

- join/combine complementary information produced by sensor to obtain a more complete picture or
- reduce/manage uncertainty by using sensor information from multiple sources." [66]

JALOBEANU AND GUTIÉRREZ (2006)
"The data fusion problem can be stated as the computation of the posterior pdf [probability distribution function] of the unknown single object given all observations." [67]

SINHA ET AL. (2006)[w*]
"The estimation fusion problem can be categorized as a class of problems in which estimates of a continuous parameter/state vector obtained by different sources are to be combined to obtain an overall estimate which in general has better accuracy." [68]

MASTROGIOVANNI ET AL. (2007)[w]
"The aim of a data fusion process is to maximize the useful information content acquired by heterogeneous sources in order to infer relevant situations and events related to the observed environment." [22]

WIKIPEDIA (2007)[d,t]
"Information Integration is a field of study known by various terms: Information Fusion, Deduplication, Referential Integrity and so on. It refers to the field of study of techniques attempting to merge information from disparate sources despite differing conceptual, contextual and typographical representations. This is used in data mining and consolidation of data from semi- or unstructured resources." [69]

"Sensor fusion is the combining of sensory data or data derived from sensory data from disparate sources such that the resulting information is in some sense better than would be possible when these sources were used individually. The term better in that case can mean more accurate, more complete, or more dependable, or refer to the result of an emerging view, such as stereoscopic vision (calculation of depth information by combining two-dimensional images from two cameras at slightly different viewpoints).

The data sources for a fusion process are not specified to originate from identical sensors. One can distinguish direct fusion, indirect fusion and fusion of the outputs of the former two. Direct fusion is the fusion of sensor data from a set of heterogeneous or homogeneous sensors, soft sensors, and history values of sensor data, while indirect fusion uses information sources like a priori knowledge about the environment and human input.

Sensor fusion is also known as (multi-sensor) data fusion and is a subset of information fusion." [28]

MSN ENCARTA (2007)[d]
"Data integration: the integration of data and knowledge collected from disparate sources by different methods into a consistent, accurate, and useful whole." [70]

ARDESHIR GOSHTASBY AND NIKOLOV (2007)[i*]
"Image fusion is the process of combining information from two or more images of a scene into a single fused image that is more informative and more suitable for visual perception or computer processing" [71]

DAS (2008)*

"High-level data fusion … is the study of relationships among objects and events of interest within a dynamic environment. The study is supported by analyses of data produced by the sensors placed within the environment. By dynamic we mean the state of the environment, and hence relationships among its objects and events, changes due to both natural/internal events and external events by players (also called actions) within the environment." [72]

RAOL (2010)[t*]

"Data fusion means combining information from several sources, in a sensible way, in order to estimate or predict some aspect of an observed scene, leading to the building of a world model of the environment […] The term information fusion (IF) is used for the fusion of any kind of data and data sources […] and is also applicable in the context of data mining and database integration. This term covers all aspects of the fusion field, except nuclear fusion or fusion of different types of music, which may be discordant." [73, p. 4]

"Data fusion [is] the process of combining or integrating measured or preprocessed data or information originating from different active or passive sensors or sources to produce a more specific, comprehensive, and unified dataset or world model about an entity or event of interest that has been observed." [73, p. 11]

CHANG ET AL. (2014)[i*]

"Image fusion is a process of combining images obtained by sensors of different wavelengths simultaneously in a view of the same scene to form a composite image. The fused image is produced to improve image content and to make it easier for the user to detect, analyze, recognize, and discover targets and increase his or her situational awareness." [74]

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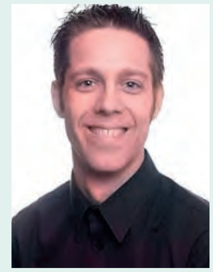

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Quantum Algorithms for Data Fusion: Trends and Applications

Abstract—Werner Heisenberg's (1901–1976) famous *Uncertainty Relation* (1927) characterizes the essence of quantum physics, which is shaping an ever-increasing number of real-world applications. While emerging quantum technologies for communication, sensing, or computing exploit quantum physical phenomena as such, quantum algorithms use the mathematical framework and numerical methods for dealing with "uncertainty", which physicists have developed over the last 100 years, to fuse data with their various "uncertainties" for harvesting actionable information. On the other hand, quantum computers may become game changers for solving classical fusion problems.

By briefly sketching examples from ongoing work at Fraunhofer FKIE, we wish to draw the attention of the international fusion community to the potential of quantum algorithms. Moreover, a special session at FUSION 2022 will provide insights into latest research.

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DATA FUSION AND QUANTUM PHYSICS

Inspiration from quantum physics seems relevant in all applications, where situation pictures, the very basis of decision-making and resources management, are produced from received signals, sensor measurements, observer reports, or context knowledge that are fundamentally "uncertain", i.e,. imprecise, incomplete, of uncertain origin, false, or corrupted, possibly unresolved, ambiguous, etc. The implementation of quantum algorithms can be well-considered on classical computers and does not necessarily imply the existence of quantum computers. On the other hand, classical data fusion problems are expected to run unprecedentedly fast on certain quantum processing kernels, anticipated with some keen foresight, as well-adapted analog computers. We therefore consider classical fusion algorithms adapted to quantum processors as "quantum algorithms for data fusion".

The class of "analog" quantum processors being referred to here is the class of adiabatic computers. It is distinct from the class of universal quantum computers that use sequences of quantum gates. Both classes are technically demanding in different ways, but the universal class is far more difficult and much less advanced than the adiabatic class. Both may have advantages. It is to be expected that quantum and classical digital computers will be coupled in creative ways to solve real problems synergistically. While we believe it to be highly unlikely that quantum computers will replace classical digital computers, quantum algorithms for data fusion may become game changers as soon as quantum processing kernels embedded in hybrid processing architectures with classical processors exist.

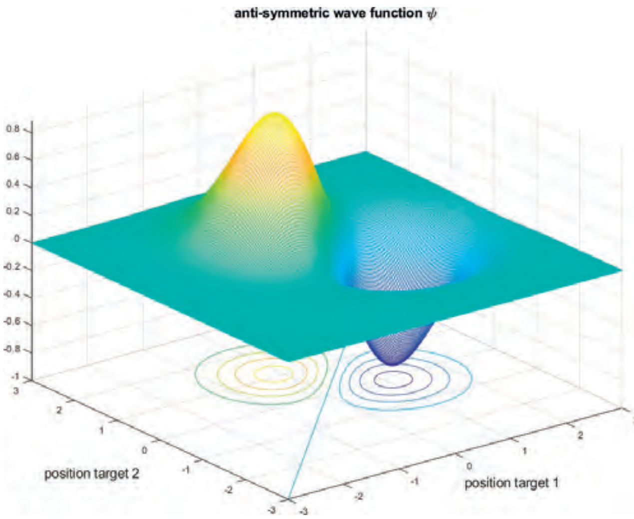
Although the link between mathematical statistics and quantum physics has long been known, the potential of physics-inspired algorithms for data fusion has just begun to be realized.

BOSONIC AND FERMIONIC TRACKING

In the macrophysical world of target tracking, objects of interest, such as airplanes, vehicles, persons, or ships are mutually distinguishable physical objects in themselves. The information on them that is collected by sensors, however, covers a limited set of their properties only and is in many cases restricted to positional and kinematic properties. Let us call targets identical if two assumptions hold: (1) their intrinsic properties cannot be distinguished from each other by the measurements considered; and (2) they move according to the same dynamical model. Spatiotemporal target properties are extrinsic by definition.

The notion of indistinguishable targets is thus natural and well-established in advanced in classical target tracking. If no specific target attributes are sensed, indistinguishability is often unavoidable and sometimes even desirable, for example, to enable "privacy by design" in public surveillance. Conceptually, this notion is rooted in quantum physics where functions of joint quantum particle states are considered that are either symmetric or antisymmetric under permutation of the particle labels. This symmetry dichotomy explains why quite fundamentally two disjunct classes of particles exist in nature: bosons and fermions.

Besides symmetry, antisymmetry also has a place in multiple target tracking, leading to well-defined probability density functions describing the joint target states. Inbuilt antisymmetry implies a target tracking version of the exclusion principle introduced by the physicist Wolfgang Pauli (1900–1958): Realworld targets are "fermions" in the sense that they cannot exist at the same time in the same state. This is of interest in dense tracking scenarios with resolution conflicts and split-off and may mitigate track coalescence phenomena, for example. Symmetry and antisymmetry can be embedded into group and extended target trackers as well, where their kinematic properties are described by random vectors, while random matrices represent their shape. Group targets might be dealt with as bosonic targets, while extended targets are typically fermions. For further details, see [1].



Tracking analog of an anti-symmetric "wave function" describing the kinematic state of two closely-spaced "fermionic" targets at a given instant of time (here: position). Anti-symmetry "forbids" identical target states.

FEYNMAN KERNELS FOR TARGET TRACKING

The temporal evolution of quantum objects is described by Erwin Schrödinger's (1887–1961) equation, which is a diffusion equation, if imaginary time variables are introduced. This analogy establishes a link to a "science of uncertainty" on a macroscopic level, i.e., statistical mechanics, which considers the temporal evolution of particle distributions driven by the random collisions with surrounding atoms or molecules. This resulting random motion was at first observed by the Scottish botanist Robert Brown (1773–1858) and stochastically explained by Albert Einstein (1879–1955).

This stochastic model is relevant in the problem of tracking objects at even larger scales. While any microscopic impact is to be neglected here, the "motion uncertainty" is still present due to insufficient knowledge on actual actions, decisions, terrain impacts, or models. Tracking theory derives algorithms to compute the stochastic properties of such systems taking "measurement uncertainty" into account due to thermal effects and imperfect observation, which is orthogonal to the process induced "uncertainties".

Path integrals, introduced by Richard Feynman (1918–1988) for solving the Schrödiger equation, reveal a conceptual link between quantum and tracking theory. Feynman's work soon was connected to the Brownian motion by the mathematician Mark Kac (1914–1984). Today, it seems well-known that path integrals provide a formulation of the tracking problem, where the measurements are represented by attracting force fields. New insights provide Accumulated State Densities [2], which enable exact formulae for the probability measures of paths and result in Feynman kernels that link starting and end points and and exploit the measurement set. Applied to a prior density, such integral kernel allows posterior densities to be computed. For linear–Gaussian models, closed formulae of Feymanian tracking kernels exist. For further details, see [3], [4].

FOCK SPACES AND INDISTINGUISHABLE TARGETS

In many particle quantum physics, the Fock spaces are useful to study systems with unknown and variable particle numbers. Introduced in 1932 by Russian physicist Vladimir Fock (1898–1974), this approach is not limited to quantum systems.

The treatment of multiple identical objects with varying numbers is also a key feature of multiple target tracking. A variety of methods has been developed in the last decades. In particular, for identical targets, approaches based on point processes and finite random sets have been derived and applied in numerous applications. As classical many particle systems and multi-target tracking have key features in common, it is interesting to compare both approaches and to apply techniques developed in one field to problems in the other. In particular, the "second quantization" approach for classical systems with its similarities (even equivalences) and differences to multi-target tracking methods are offering new insights and open the way to apply field theoretic techniques to multi-target tracking.

This correspondence includes representations of multi-object states, symmetrized probability densities for indistinguishable objects, set integrals, expectation values of linear operators, and probability generating functionals. The Bayesian measurement update can be integrated into the overall scheme. For further details, see [5].

QUANTUM ALGORITHMS FOR DATA FUSION

Due to ambigious data interpretations, the multiple target tracking problem is well-known to be NP-hard on classical computers. The exponential growth in the number of combinations over time is the reason why a full exploitation and consideration in the hypothesis space seems infeasible in practical applications. Recent advancements suggest that quantum computing may soon see applications, where the quantum state can be turned into the optimal solution of problems, which correspond to the eigenstates of a Hamiltonian with the lowest eigenvalues. The multiple target data association problem, a complex nonlinear integer programming optimization task, belongs to this class.

In the adiabatic quantum computing approach, the Hamiltonian of the system is a time dependent convex combination of a trivial beginning Hamiltonian and the desired end-state. The evolution of the system is governed by the Schrödinger equation, while the dynamics of the Hamiltonian must be slow enough ("adiabatic") in order to keep the quantum system in the lowest energy state. Furthermore, it is required that the time-dependent Hamiltonian has a spectral gap between the lowest and second lowest eigenvalues for all instants of time. Under these conditions, a solver for the single target data association problem can be derived that can be executed on state-of-the art adiabatic quantum processing hardware. The underlying principle is closely related to solving to so-called *k*-rooks problem, i.e., the problem of placing k rooks on a $k \times k$ chess board without the pieces threatening each other. Even though the single scan data association problem is not NP-hard (in contrast to the multi-scan problem), the principle can well be extended to more complex problems. The fundamental concept of data association can thus be solved using adiabatic quantum computing. For further details, see [6].

PERSPECTIVES FOR RESOURCES MANAGEMENT

Adiabatic quantum computing also enables solving the well-known weapon-to-target assignment problem, an NP-hard nonlinear integer programming task. This optimization problem draws great interest in operations research and deals with the general issue of optimized assignment of m weapons or workers to n targets or tasks, based on the probabilities of successful task completion and the (threat) value of the given targets or tasks. The solution is not limited to the context of weapon management but is, with slight modifications to the model Hamiltonian, applicable also to optimal sensor allocation. Due to the underlying physical structure of adiabatic quantum computation hardware, these devices are best-suited to solve quadratic unconstrained binary optimization problems or Ising models. It is thus necessary to reformulate and/or approximate these problems given optimization objectives in terms of an Ising model. For further details, see [7].

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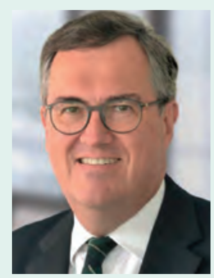

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Agents with Free Will: A Theory Grounded in Quantum Physics

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***Abstract*—**Does free will exist? It feels that way. We experience choosing freely among different possible actions, and these choices seem to have effects in the world. Yet the mainstream view among scientists is that our choices are entirely a function of neurobiological processes unfolding according to the laws of physics. Our intentions, the argument goes, play no causal role in our actions except as a high-level description of complex, underlying, physically determined processes in our brains and bodies. If this mainstream view were overturned, the implications for human society and for artificial intelligence would be profound. This paper explores a scientifically well-founded theory in which intentionality plays a fundamental causal role in our behavior. We begin by defining a set of properties that formalize the concept of genuine free will. We then present a theory of agency that satisfies these properties and is fully consistent with the laws and precepts of quantum physics. Next, a roadmap is given for evaluating the theory. Finally, implications for science, engineering, and philosophy are discussed.

INTRODUCTION

Imagine that you are feeling thirsty on a hot summer day. You see an ice-cold, sugary drink sitting enticingly on a nearby table. You can almost taste it. You wage an internal battle between your thirst and your recent resolution to cut down on sugar intake. You think about reaching over for the drink, but hesitate. Which do you choose? The delicious, thirst-quenching drink or your health? As you struggle with the decision depicted in Figure 1, it certainly feels as if both choices are physically possible. After you have chosen and acted on your choice, it feels as if it would have been possible to have chosen otherwise. It feels as if *you* are the one who made the choice and caused the outcome. Who is this *you*? Is the feeling that you make genuine choices real or an illusion?

Figure 1
Shall I take a drink?

The mainstream view in science and philosophy is that your feeling of choosing freely is not physically accurate. Just as our intuition of a flat earth has been superseded by a more accurate scientific theory, mainstream science tells us our intuition of having free will has been superseded by a more accurate scientific understanding of neurobiological processes. Like a robot executing a program, our choices are the result of neurobiological processes unfolding according to effectively deterministic physical laws. Pearl and Mackenzie [1] posit that the "illusion of free will" gives us an evolutionary advantage by enabling a compact high-level representation of goals, actions, and priorities. We perform better and learn more efficiently if we use a shorthand representation in which detailed micro-level instructions are encoded in terms of a few high-level options. Indeed, we adopt a similar shorthand when talking about computer programs: rather than describing the details of algorithm execution, we say the loan processing system "decided" to reject an application because of missed car payments, or the robot "chose" to take the longer route to avoid an obstacle.

Are our choices like those of a computer program? Is our experience of making free choices no more than a shorthand encoding of complex but effectively deterministic physical processes in our brains and bodies? This presumption is not as airtight as many assume. Klemm [2] lists twelve major interpretative problems with experiments purporting to support the "zombie argument" that our conscious minds are passive spectators to unconsciously generated actions. Lavazza and De Caro [3] argue that many claims of neural determinism are overstated. On the theoretical side, Stapp [4], [5] argues that genuine, efficacious free will is fully compatible with a realistic interpretation of quantum physics. He argues that there are complementary explanatory gaps in psychology and physics that can be filled by positing an interaction between the brain's quantum state and our mental experience when we make a choice. This interaction provides an opening for efficacious free choice that is fully consistent with the laws of quantum theory [6], [7]. Thus, Stapp argues, genuine free will is fully compatible with our present-day understanding of physics.

The remainder of this article expands on this idea. Section "Free Will Postulates" sets forth properties that formalize a commonsense notion of free will. Section "Free Choice by Physically Embodied Agents" presents a theory of free will that satisfies the postulates given in the Section "Free Will Postulates" and is fully compatible with the laws of physics. Section "Evaluating The Quantum Reducing Agent Hypothesis" describes a path to scientific evaluation of the theory. Finally, implications for science, society, and the future of artificial intelligence are discussed.

FREE WILL POSTULATES

Arguments about free will often center on whether a notion of free will can be defined that is compatible with effectively deterministic micro-level decision-making processes. Any suggestion that there may be something more to our feeling of free will is dismissed as incompatible with science. The objective of this paper is to formulate a theory of free will that is both compatible with our intuitions and scientifically viable. This requires a clear definition what is meant by the term "free will." The following postulates, taken from [8], are intended to capture and formalize fundamental intuitions of what it means for an agent to have free choice. A similar set of properties is proposed in [9]. An *agent* is defined as a physical system that makes choices satisfying these *free will postulates*:

P1. *Freedom*. There are occasions, called *choice points*, at which multiple alternatives for an agent's future behavior are possible.

P2. *Attribution*. At each choice point, the agent's free choice determines which of the possible alternatives occurs.

P3. *Efficacy*. Choices are efficacious in the sense that the alternative taken at a choice point causes effects in the physical world that are different from what would have occurred had a different alternative been chosen.

P4. *Physicality*. The choices agents make and the effects they have in the world are consistent with the laws of physics.

Many scientists and philosophers take as a given that these properties are mutually inconsistent. P4, the physicality condition, seems to imply determinism, perhaps accompanied by randomness at the quantum level. Determinism violates P1. Randomness violates P2. Compatibilists argue that P1 and P2 should be understood not as actual physical properties, but as our cognitive level experience. That is, our behavior is *actually* mostly deterministic with a bit of quantum randomness, but we *experience* ourselves to be making choices.

In truth, properties P1–P4 are mutually consistent. All four postulates are satisfied by Stapp's [6] theory of free will, which is founded on a realistic interpretation of von Neumann's [10] formulation of quantum theory. The following sections formalize this theory of how mental intentions give rise to bodily actions.

In addition to Properties P1–P4, two additional postulates are needed for a theory of free choice in intelligent, physically embodied agents. Postulates P5–P6 below generalize to arbitrary agents the postulates for human agents presented in [8].

P5. *Representation*. In a manner compatible with their physical architecture, intelligent, physically embodied agents can form representations of the world. They are able to manipulate these representations to predict the effects of the available options and compare the desirability of different options.

P6. *Implementation*. In a manner consistent with their physical architecture, intelligent, physically embodied agents can enact their choices to cause their bodies to behave as intended.

Properties P5 and P6 capture the requirement that intelligent agents are *physical symbol systems* in the sense of Newell and Simon [11]. For biological agents, the physical architecture refers to neurobiological processes in their brains and bodies. For robotic agents, free will would require physical hardware compatible with P5 and P6. What constitutes such a physical architecture is an open scientific question.

FREE CHOICE BY PHYSICALLY EMBODIED AGENTS

Our experience of having free will is undeniable. We experience our choices as having a causal impact on the world, and *our freely chosen intentions* as the cause of the choices we make. Postulates P1–P4 formalize the intuition behind the notion of free choice. This section shows that these four postulates are consistent with quantum theory and can provide the basis for a theory of agency in nature.

CAUSAL MARKOV PROCESSES

A scientific theory of agency requires a formal representation of the alternative actions agents can take and how they affect the world. To that end, causal Markov processes provide a formal language for representing the choices of agents and their effects on the environment.

Definition 1: *A (time-invariant, first-order, discrete) causal Markov process is a family of stochastic processes specified by the 3-tuple* (S,A,π)*, where* S *is a state space,* A *is an action space, and* π *is a transition distribution, such that the following conditions are satisfied:*

1. *For each* $s,s' \in S$ *and* $a \in A$*, the function* $\pi(\cdot|s';a)$ *is a discrete probability measure on* S*.*

2. *Given an initial state* s_0 *and conditional distributions* $\theta(a_k|h_k)$*,* $k = 1,\ldots,n$ *for selecting actions conditional on*

the past history $h_k = (a_1,a_2,...,a_{k-1},s_0,s_1,s_2,...,s_{k-1})$ of actions and states, the joint distribution for the sequence $(a_1,a_2,...,a_n,s_1,s_2,...,s_n) = (\boldsymbol{a},\boldsymbol{s})$ of actions and states satisfies:

$$\mathrm{P}(\boldsymbol{a},\boldsymbol{s} \mid s_0) = \prod_{k=1}^{n} \theta\left(a_k | h_k\right) \pi\left(s_k | s_{k-1}, a_k\right). \tag{1}$$

3. *An intervention* $do(a_k = a^*)$ to replace $\theta(a_k|h_k)$ *with the distribution* $1_{[a_k=a^*]}$ *that places probability 1 on* a^**, changes the joint distribution to:*

$$\mathrm{P}(\boldsymbol{a},\boldsymbol{s} \mid s_0) = \pi\left(s_k | s_{k-1}, a^*\right) 1_{\left[a_k=a^*\right]} \prod_{j \neq k}^{n} \theta\left(a_j | h_j,\right) \pi\left(s_j | s_{j-1}, a_j\right), \tag{2}$$

Here, the index k represents choice points at which actions may be taken. The actions $a \in A$ represent interventions taken by an agent that affect future evolution of the system. The states $s \in S$ capture all aspects of the agent and the environment relevant to predicting future states and how they are affected by actions. Equation (1), called the causal Markov condition, implies that the most recent past state and the action taken at the next choice point capture all aspects of the world relevant to predicting the next state. Equation (2) formalizes how interventions work. The notation $do(a_k = a^*)$ represents an intervention to set the action at the kth choice point to have value a^*. The effect of an intervention is to replace the "unperturbed" probability distribution $\theta(a_k|h_k)$ with the distribution $1_{[a_k=a^*]}$ that assigns probability 1 to a^*. Interventions satisfy a locality condition: the only effect on the evolution of the system is to set the kth action to a^*. All other causal mechanisms remain unchanged [12]. The mapping $\theta(a_k|h_k)$ from the history to a probability distribution on the next action a_k is called the agent's policy. The distribution $\pi(s_k|s_{k-1},a_k)$ for the next state conditional on the previous state and the next action is called the transition distribution.

Our theory of free will ascribes the choice of policy $\theta(a_k|h_k)$ to the agent, subject to relevant physical constraints. The transition distribution is ascribed to nature, and in multi-agent problems, the actions of other agents. In other words, Equation (1) specifies how the states of the agent and environment evolve, under the agent's chosen policy, the transition distribution chosen by nature, and the policies chosen by other agents. Equation (2) specifies counterfactual probabilities for the evolution of the agent and environment if the agent were to make different choices.

QUANTUM THEORY BASICS

Prior to the advent of quantum theory, the evolution of the physical world was thought to be deterministic. Early in the 20th century, this classical picture was definitively overturned by the explicitly probabilistic quantum theory. The formal mathematical foundation for quantum theory was developed by von Neumann [10] in the 1930s. While there is a multitude of ways to interpret the mathematics, von Neumann's formalism remains the standard textbook presentation of quantum theory (e.g., [13], [14]).

The mathematical theory associates a characteristic Hilbert space $\mathcal{H}$ with each quantum system. A Hilbert space is a complex inner product space that is complete with respect to the norm induced by the inner product. The state of a quantum system is represented by a density operator on $\mathcal{H}$, that is, a self-adjoint, positive semidefinite operator with unit trace. A state can be represented as a complex-valued, possibly infinite-dimensional, matrix that is equal to its conjugate transpose, and has real, non-negative diagonal elements that sum to 1. Density operators can represent pure states, statistical ensembles of states, and/or subsystems of a composite quantum system.

A quantum system undergoes two distinct kinds of evolution. The first is continuous, deterministic, mechanical evolution of the quantum state. The second is a stochastic transformation called *reduction*, *measurement*, or more picturesquely, *collapse*.

During mechanical evolution for d>0 time units, the initial state ρ transforms to $\mathcal{A}_d\rho$, where $\mathcal{A}_d$ is a completely positive, trace-preserving (CPTP) map that is continuous in d and satisfies $\mathcal{A}_0\rho = \rho$. The CPTP map $\mathcal{A}_d$ depends on the system's environment. For simplicity, the discussion that follows assumes a time-invariant environment, but with appropriate modifications the theory applies to time-varying environments. Reduction corresponds to application of a self-adjoint, bounded operator R to the pre-reduction state ρ. The reduction operator can be decomposed as $R = \Sigma_r rP_r$, where the r are real-valued eigenvalues of R and the P_r are mutually orthogonal projection operators summing to the identity. That is, $P_r^2 = P_r$ for each r; $P_rP_s = 0$ for $r \neq s$; and $\Sigma_r P_r = I_{\mathcal{H}}$. When a reduction occurs, one of the eigenvalues r is selected with probability $q_r = \mathrm{Tr}(P_r\rho P_r)$, where $\mathrm{Tr}(\cdot)$ denotes the trace. When r is selected, the state instantaneously and discontinuously transforms into the post-reduction state 1/ $(1/q_r)P_r\rho P_r$.

Quantum theory specifies the rules for evolution between reductions and the probabilities of post-reduction outcomes. However, there is no theory to predict when reductions will occur or which of the allowable reduction operators will be applied. Phenomenologically, reductions have been associated with measurements taken by scientists to observe the system. For this reason, this fundamental gap in quantum theory has been called the "measurement problem".

The mathematics of quantum theory is undisputed, and its probabilistic predictions have been verified to great accuracy. Nevertheless, there has been intense debate over the ontological status of reductions. The many-worlds interpretation asserts that reductions do not actually occur. Instead, each outcome occurs in its own world with its own observers. The question of why we observe only one outcome in our world has not been answered satisfactorily. Realistic interpretations assert that reductions do occur. There have been different proposals to fill the explanatory gap for how and when reductions occur, none of which has gained broad acceptance or achieved empirical confirmation. The Copenhagen interpretation eschews ontological claims, focusing instead on pragmatic rules for predicting the outcomes of experiments.

QUANTUM THEORY AS A CAUSAL MARKOV PROCESS

The popular conception of quantum theory, with its emphasis on randomness, would seem to provide no room for decision-making. As Searle [15] put it, "It is true that there is an indeterminacy in nature at the quantum level, but that indeterminacy is pure randomness and randomness is not by itself sufficient to give free will."

Yet, randomness is not the whole story. Although it is not widely appreciated, quantum theory can be formulated as an interventionist causal theory [16] with reductions as interventions. As Bohm [17] put it, the quantum state has been called a wave of probability, but it is more accurately described as a "wave from which many related probabilities can be calculated". In other words, quantum theory predicts not a single probability distribution for what will occur, but rather a family of probability distributions, one for each choice of when a reduction occurs and what operator is applied. If the choice of reduction is ascribed to the free will of the agent, this yields a formal theory satisfying properties P1–P4.

Specifically, the *quantum reducing agent hypothesis* (QRAH) postulates that the universe contains systems, called *quantum reducing agents*, that can cause reductions to some parts of their own physical states. According to the QRAH, selection of a policy for initiating reductions is chosen according to the quantum reducing agent's free will. Formally:

Definition 2: *A quantum reducing agent (QRA) is a causal Markov process with state space, action space, and transition distribution as given below, where the choice of actions is ascribed to the agent's free will.*

- *State space*: *The states of a QRA are density operators on the Hilbert space $\mathcal{H}$ of the quantum system.*
- *Action space*: *The allowable actions in a QRA are tuples $<d,R>$, where d is a positive real number representing the time until the next reduction and R is a self-adjoint, bounded operator.*
- *Transition distribution*: *Let ρ be the state just after the previous reduction, d the time until the next reduction, $\mathcal{A}_d$ the CPTP map representing mechanical evolution, and R the reduction operator applied after d time units. The initial state ρ evolves mechanically to $\mathcal{A}_d\rho$, at which point the state transitions abruptly to the outcome associated with one of the eigenvalues r. The probability of eigenvalue r is given by $q_r = \mathrm{Tr}(P_r\mathcal{A}_d\rho P_r)$. The post-reduction state if r occurs is $\rho_r = (1/q_r)P_r\mathcal{A}_d\rho P_r$. The possible outcomes ρ_r are mutually orthogonal.*

A QRA chooses a policy, or rule for selecting a time at which to initiate the next reduction and an operator to apply. If the system starts at initial state ρ and evolves mechanically for time d_1+d_2, the resulting state will be $\mathcal{A}_{d_1+d_2}\rho$. This is the same state that would occur if the no-intervention actions $<d_1, I_{\mathcal{H}}>$ and $<d_2, I_{\mathcal{H}}>$ had been applied to the initial state ρ. If the "null" action $<d_1, I_{\mathcal{H}}>$ is replaced by the intervention $do(a_1 = <d_1,R_1>)$, where R_1 is a reduction operator, the result is mechanical evolution to $\mathcal{A}_{d_1}$, then a stochastic transition to $(1/q_r)P_r\mathcal{A}_{d_1}\rho P_r$ with probability $q_r = \mathrm{Tr}\left(P_r\mathcal{A}_{d_1}\rho\, P_r\right)$, followed by mechanical evolution to $\mathcal{A}_{d_2}(1/q_r)P_r\mathcal{A}_{d_1}\rho\, P_r$. In general, applying a reduction at any time point causes a stochastic transition at that point, followed by mechanical evolution of the resulting state from that point. This process is illustrated in Figure 2.

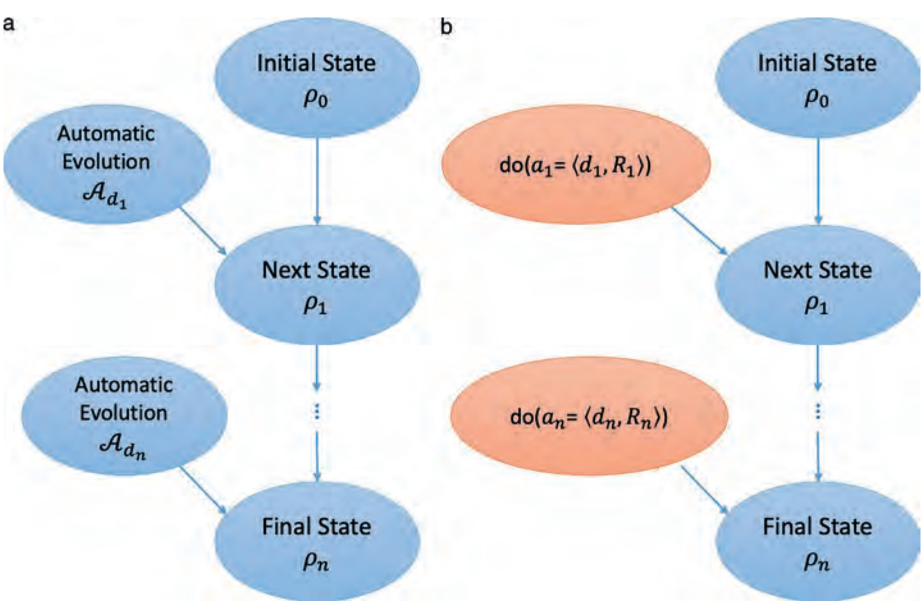

Figure 2

Quantum theory as interventionist causal theory: (a) With automatic evolution, ρ_k has value $\mathcal{A}_{d_k}\rho_{k-1}$ with probability 1; (b) On intervention $do(a_k = <d_k,R_k>)$, the state ρ_{k-1} transforms to $\rho_k = (1/q_r)P_r\mathcal{A}_{d_k}\rho_{k-1}P_r$ with probability $q_r = \mathrm{Tr}\left(P_r\mathcal{A}_{d_k}\rho_{k-1}P_r\right)$.

There is a key difference between reductions as typically described in textbooks and the QRAH. Textbooks usually describe measurements a scientist makes on a quantum system undergoing experimental manipulation. That is, the scientist causes a reduction applied to an external system and observes the result, thereby gaining information about the external system. In contrast, the QRAH postulates that a reducing agent causes reductions not directly to an external system, but to *some part of its own physical state*. The two descriptions can be reconciled by recognizing that the scientist's body and the measurement instrument are coupled systems. Thus, if the scientist can effect a reduction to her own physical state that causes her motor cortex to initiate movement of her arm and hand, the hand can then move the control knob on an instrument, which thereby causes a reduction of the physical state of the external quantum system. This chain of coupled systems, from the scientist's brain to her body to the external system, is described clearly by von Neumann in his discussion of measurements. The chain ends in subjective perception of the measurement outcome. Subjective perception is, according to von Neumann,

> *…a new entity relative to the physical environment and is not reducible to the latter. Indeed, subjective perception leads us into the intellectual inner life of the individual, which is extra-observational by its very nature. [10], p. 418.*

The quantum reducing agent hypothesis postulates that free will operates via application of state reductions by systems called quantum reducing agents. These agents possess the ability to initiate reductions to some part of their own physical state. They exert free will by choosing which of their available reduction operators to apply at what times. This choice is, to use von Neumann's words, "extra-observational" and is ascribed to the "inner life" of the agent.

The QRAH satisfies postulates P1–P4:

P1. *Freedom*: As currently understood, the laws of physics specify how a quantum system evolves when not subjected to reductions, as well as the probability distribution of outcomes given the reduction operator and time of application. That is, quantum theory specifies the following dynamical laws:

a. $\rho \to \mathcal{A}_d \rho$ if mechanical evolution occurs for d time units; and

b. $\rho \to (1/q_r)(P_r \mathcal{A}_d \rho P_r)$ with probability $q_r = \mathrm{Tr}(P_r \mathcal{A}_d \rho P_r)$ if reduction operator R with spectral decomposition $R = \sum_r r P_r$ is applied immediately following mechanical evolution for d time units.

The known laws of physics place no constraints on the choice of time interval d or self-adjoint, bounded operator R. Modulo as yet undiscovered limits on d and R, there are multiple allowable choices of action $\langle d,R \rangle$. Therefore, there are multiple possible options at each choice point.

P2. *Attribution*: QRAH attributes the choice of action $\langle d,R \rangle$ to the reducing agent.

P3. *Efficacy*: The choice of action has empirically distinguishable effects in the physical world, as depicted in Figure 2 and confirmed by extensive experimentation.

P4. *Physicality*: RAH is fully consistent with the known laws of physics as formalized by von Neumann [10] and universally accepted by the scientific community.

By virtue of satisfying P1–P4, QRAH qualifies as a viable candidate theory of efficacious choice by physically embodied agents. We go beyond this basic theory to hypothesize further that QRAs include humans and other life forms, and may also include other kinds of systems in the natural world. In the specific case of human free will, QRAH postulates that human agents make free choices by initiating reductions to some part of their own bodies. Because the cerebral cortex appears to be responsible for cognition and decision-making, it is natural to hypothesize that human QRAs are able to initiate reductions in the cerebral cortex, and specifically in the motor cortex. How, specifically, might such capability be effected in human brains? The next section addresses this question.

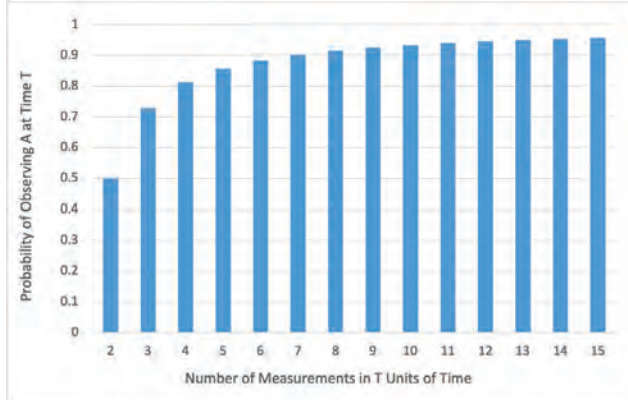

Figure 3

Rapid measurement holds quantum system at same state.

FREE WILL AND THE QUANTUM ZENO EFFECT

Quantum theory textbooks describe reductions as interactions between inanimate microscopic quantum systems and inanimate measuring devices to produce measurements that are observed by scientists. While the founders of quantum theory stressed that the decision of when to initiate a measurement and which measurement to take should be assigned to the free choice of the scientist, they did not consider how such a free choice might be formulated within the scientist's brain and then executed by the scientist's body. In the mathematical formalism of quantum theory, the choice of measurement is free in the specific sense that the theory provides no rules for how the choice is made. Stapp [6] suggests that this gap could be filled by postulating that humans, and possibly other QRAs, have the ability to make free choices by initiating quantum state reductions to some part of their own bodies.

James [18] said, "The essential achievement of the will… is to attend to a difficult object and hold it fast before the mind... Effort of attention is thus the essential phenomenon of will." Stapp suggests that it is this "effort of attention" where quantum theory may play a role. He postulates that Jamesian effort of attention occurs through an essentially quantum phenomenon called the quantum Zeno effect (QZE), whereby rapid repeated reductions applied to a quantum system change its observable behavior [19].

To understand how the quantum Zeno effect works, consider a simple example in which a system is measured and outcome A is observed. The system is then allowed to evolve undisturbed for a period of time, at which point the measurement is repeated. Suppose the system is allowed to evolve for T units of time, and a sequence of measurements, each of which has A as a possible outcome, is taken at equally spaced moments between times 0 and T. Figure 3, taken from [7], shows the probability, in a simple example system, of observing A at the last measurement as a function of how many measurements are taken between 0 and the time of the last measurement. The more measurements are taken, the higher the probability that *A* will be observed at the last measurement. If enough measurements are taken, the system is effectively frozen in place, and the result *A* occurs with probability near 1. This effect of freezing a system in place by rapid measurement has been verified in the laboratory [20].

Rapid measurement can also be used to drive a quantum system to a desired state [10]. Because it can be used to accelerate rather than slow down evolution of a quantum system, this phenomenon has been called the inverse quantum Zeno effect [21]. Whereas the quantum Zeno effect involves repeated applications of the *same* reduction operator, the inverse quantum Zeno effect uses a sequence of *different* reduction operators, having a sequence of outcomes along a path from the initial to the desired outcome. If such a sequence of operators is applied in rapid succession, the probability is high that the system will follow this path, resulting in the desired state at the end of the process.

The Section "Quantum Theory as a Causal Markov Process" demonstrated that a QRA as specified in Definition 2 satisfies properties P1–P4. Such a QRA can make choices by initiating reductions to some part of its own body. Stapp further suggests QZE operating in the cerebral cortex as the mechanism by which humans take volitional action. This additional hypothesis requires a model of QZE in the cerebral cortex that is consistent with scientific findings on the neurobiology of volitional action in humans.

A common criticism of quantum theories of mind is that decoherence [22], which occurs when quantum systems interact with their environments, would rapidly destroy quantum effects in the brain. Although environmental decoherence does destroy quantum interference, it is important to note that the quantum Zeno effect survives decoherence [5], and thus could plausibly operate in animal brains. Specifically, a theory of free will in humans must satisfy properties P5 and P6. That is, we require a model of volitional behavior operating through QZE that can be effected in human brains.

EVALUATING THE QUANTUM REDUCING AGENT HYPOTHESIS

To flesh out this theory, it is necessary to develop a concrete model of how reductions are employed to effect purposive behaviors. Once such a model has been formulated, it must be evaluated empirically. We consider three research thrusts to achieve this objective: simulation, laboratory studies, and hardware implementation. This section is taken, with light edits, from [8].

SIMULATING A REDUCING AGENT

Stapp proposes, based on research in neuroscience of animal behavior, that the brain learns complex patterns of neurological activity that he calls templates for action. When such an action template is executed, a sequence of nerve signals is sent to the muscles, causing bodily movements. These movements can be adjusted during execution in response to inputs from the senses. The processes of learning and executing these action templates is well described by standard models in neuroscience, e.g., [23]. Where quantum theory plays an essential role, according to Stapp, is to hold an action template in place for longer than it would through purely automatic execution. Thus, the brain automatically retrieves an action template, and QZE is then applied to hold it in place long enough to execute the associated behavior. This model is consistent with the well-established time lag (e.g., Libet [24]) between neural activity associated with a decision and conscious awareness of the decision. An action template is called up prior to conscious awareness of making a decision. The agent then either applies QZE to reinforce the decision or disrupts execution of the action template.

Synchronous oscillations of activity in the brain's neural network appear to play an important role in cognitive processes [25]–[27]. Synchronicity has been hypothesized as a mechanism for how the brain binds component features into representations of composite objects. For example, *in vivo* studies in behaving animals have found that neurons responding to individual features begin firing synchronously when the animal recognizes that the features form a coherent object [28]. Synchronous oscillations also appear to play an important role in motor control [29], preparation for motor activity [30], sensory motor coordination, and focused attention [26]. These findings suggest that templates for action may be characterized by periods of synchronous oscillation in areas of the brain associated with the action to be executed.

Other research suggests a feedback relationship between neural activity and the brain's electrical field [31], [32]. Externally applied electromagnetic (EM) fields have been found in laboratory studies to affect neural activity, and are used in a clinical setting to diagnose and treat a range of neural disorders. Fröhlich and McCormick [31] studied the brain's endogenously generated electric field in a series of *in vivo* experiments and in a computational simulation. Their findings provide evidence of a feedback process in which endogenous electric fields act in a feedback process in which synchronous oscillations increase the strength of the brain's electric field, which in turn reinforces synchronicity of oscillations. Several authors have suggested the brain's electric field as the locus for consciousness (e.g., [4], [33]–[35]). Although the EM field hypothesis is considered speculative, its proponents argue that it explains how information distributed among millions of neurons is unified into coherent percepts. Regardless of the role played by the electric field in consciousness, its role in entraining synchronicity in neural activity appears to be important.

In light of the important role played by oscillations in the brain's electric field, Stapp ([6], Appendix F) developed a simple model of the use of QZE to control the strength of the electric field. His model employed a single frequency quantum oscillator at 20 Hz. The choice of frequency was based on an experimental study that found beta range (15–30 Hz) oscillations in the motor cortex of trained monkeys approximately 100 ms after the monkeys were instructed to move [36]. He also noted that beta oscillations in cortical minicolumns are at the quantum scale [37], thus suggesting the possible relevance of quantum effects. His single frequency oscillator model can be solved exactly, being a natural extension of the classical simple harmonic oscillator. His analysis demonstrated that the inverse quantum Zeno effect can be applied to increase the amplitude of the quantum oscillator. He calculated the rate of reductions required to have a high probability of increasing the amplitude and concluded that the time scale was reasonable for the neuroscience domain. The amplitude of oscillation corresponds to the strength of the electric field. Thus, Stapp's stylized model demonstrates that the inverse quantum Zeno effect can be applied to increase the strength of the electric field, which in turn would enhance synchronicity in oscillations in the brain's neural network.

Stapp's model considered the oscillating electric field in isolation, without considering how it affects and is affected by synchronicity in neural firing. His model, while suggestive that the QZE could be employed in scenarios consistent with known neuroscience, needs to be extended to a more realistic neurodynamic model.

A potential avenue of research would be to formulate a model that explicitly considers the interaction between the electric field and the spreading activation process in the neural network. The Fröhlich and McCormick model [31] does just this. The model contains some stochastic elements, but is not quantum. Adding quantum effects to a model like this would yield a concrete, biologically plausible model that could be used to investigate the quantum reducing agent hypothesis. Such a model could be used to examine whether rapid reductions can generate macroscopically distinguishable effects on synchronicity of neural activity at biologically realistic parameter settings. The rate of application of state reductions could be included in the model as an adjustable parameter. Reductions could be employed to nudge the brain toward synchronous firing of neurons associated with an action template the organism intends to execute, or to disrupt synchronous firing and thus interrupt an action template the organism intends to discontinue.

Once such a model was developed, it could be implemented on a computer and systematic experimentation could be performed to investigate whether the rate of reduction can be adjusted to entrain or disrupt synchronicity of neural firing. Once neurons are firing synchronously, are there rates of reduction, i.e., "attention density settings", that either reinforce or disrupt synchronous firing? If neurons are not firing synchronously, can "attention density" be employed to generate synchronicity? These and other pertinent questions could be addressed through computational experiments.

It should be noted that the kind of simulation envisioned here should have similar computational complexity to models commonly used in neuroscience. Because environmental decoherence suppresses quantum interference, the quantum neurodynamic model could be approximated as a probability mixture of near-classical possibilities. In other words, extending the approach taken by Stapp in Appendix F of [6], it should be possible to model QZE by modifying a standard stochastic neural network model, thus avoiding the computational difficulties of representing and simulating high-dimensional density operators.

If computational experiments demonstrated that different "attention density settings" produced clearly distinguishable differences in synchronicity using biologically realistic parameter settings, it would lend support to the reducing agent model of efficacious choice.

LABORATORY STUDIES

Previous sections have articulated a set of hypotheses about how reducing agents may influence the world through the application of QZE. Specifically, the templates for action that guide automatic processing appear to involve waves of synchronous oscillation of relevant parts of the brain's neural network in a feedback relationship with the brain's endogenous electric field. It is hypothesized that QRAs apply QZE to hold desired action templates in place and to apply fine-tuned guidance for their execution. This suggests that rapid reductions would occur in parts of the brain associated with intentional action, and would be employed to increase synchronous firing of neurons associated with action templates the agent intends to implement.

The Section "Causal Markov Processes" proposed developing concrete mathematical models for how QZE influences synchronous firing in neural networks. Such modeling should be informed by laboratory research on the structure and behavior of biological neural networks. Computational experiments with the resulting models could be used to examine the biological plausibility of the hypothesis that efficacious choice operates via the quantum Zeno effect. If successful, these computational experiments should give rise to predictions about the biological mechanisms underlying volition, attention and motor control. These predictions could be tested in laboratory experiments on animals. Results from the laboratory could then be used to refine the computational models and generate additional predictions for further laboratory experiments. The resulting feedback cycle would, if successful, increase our understanding of the neurobiological processes underlying volitional action.

HARDWARE IMPLEMENTATION

Intelligent agents form representations of the world around them, learn better representations through environmental feedback, manipulate their representations to predict the consequences of different actions, and use these predictions to take intentional action. These representations are formed and manipulated in a physical substrate. Artificial intelligence (AI) has taken the computational metaphor as a given and assumed that the physical substrate of digital computers is sufficient for intelligent behavior. AI has thus pursued the objective of building artificially intelligent agents executing on digital computers.

If the reducing agent hypothesis is correct, then the best that can be hoped for with present-day digital computer systems is a simulation of intelligence. These simulations have performed extremely well on some tasks and less well on others. The reducing agent hypothesis suggests that at least some of the failures may be due to intrinsic limitations of digital computers.

Under the reducing agent hypothesis, achieving true engineered intelligence would require a physical substrate capable of supporting efficacious action through the employment of reductions. That is, an agent's cognitive and motor architecture must be instantiated in a physical structure that can produce macroscopically distinguishable behaviors from different policies for applying reduction operators. The agent must also have a sensory apparatus to convey the real-world results of behavior to a learning system capable of refining the agent's world representation in response to environmental feedback. Research on computational simulations, informed by animal experiments, could inform hypotheses about the kind of physical substrate needed for reducing agents. This research program, if successful, could ultimately lead to engineered intelligence that is more than a simulation.

DISCUSSION

The stakes in the debate over free will are high. Absent free will, is there any moral basis for expecting socially adaptive behavior or assigning personal responsibility for our actions? Would widespread belief that free will is an illusion lead to nihilism and social dissolution? As Smilansky, quoted in [38], put it, "We cannot afford for people to internalize the truth" about free will. But what if Smilansky's "truth" is not actually true? Is it not critical for science to investigate this question?

It turns out that the four commonsense postulates of freedom, attribution, efficaciousness, and physicality are indeed mutually compatible. All four postulates are satisfied by a realistic interpretation of quantum theory in which physically embodied agents can cause quantum state reductions to some part of their physical states.

Two additional postulates, representation and implementation, must be satisfied by physical symbol systems. Such physical symbol systems might be the "new entity" von Neumann associated with the "intellectual inner life of the individual." That is, causing reductions in the cerebral cortex via the quantum Zeno effect might be the way the "intellectual inner life of the individual" is empowered to make free choices and implement them in the physical world.

The theory presented here is consistent with the known laws of physics, but must be regarded as provisional until it is further fleshed out into a concrete model of behavior in biological systems, and then evaluated empirically. Whatever the ultimate verdict, the profound implications of a physically grounded theory of free will argues for taking the quantum reducing agent hypothesis seriously enough to devise and conduct such tests of its plausibility. Computational experiments could be used to evaluate its consistency with known results in neuroscience. Such experiments could lead to laboratory experiments on animals, and ultimately to a better understanding of decision-making in biological agents.

The implications of the quantum reducing agent hypothesis for the future of artificial intelligence are even more profound. The prevailing view in artificial intelligence is that classical computing theory is an adequate foundation for artificial intelligence. Research in quantum computing focuses on achieving coherent superpositions of many qbits. In contrast, the quantum reducing agent hypothesis suggests that an appropriate physical substrate for engineered intelligence might be an artificial neural network at the edge of the quantum scale that is well-approximated by a classical probability mixture. According to the theory presented here, this is the kind of system that could possess an ability to initiate and control reductions to its own physical state. Computational experiments like those suggested above might give insight on the physical properties required for such a system. This would provide a theoretical basis for intelligent robotic agents with the ability to make genuine free choices.

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Call for Papers

JAIF 22

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A semi-annual archival publication of the International Society of Information Fusion

The Journal of Advances in Information Fusion (JAIF) is the flagship journal of the International Society of Information Fusion (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 and includes two issues each year. The journal is indexed at SCOPUS, free for authors, and freely available for readers at

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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.

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At the time of submission to JAIF, any previous publication (or submission) that includes more than 25% of the material in the paper must be declared by the authors. Manuscripts are submitted at

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ISIF

ISIF AWARDS

ISIF AWARD PROGRAM

To encourage excellence and advancements in the research community for information fusion, the International Society of Information Fusion (ISIF) sponsors awards for significant achievements in the field of information fusion. In addition to the two best paper awards [see p. 28], the Yaakov Bar-Shalom Award for a Lifetime of Excellence in Information Fusion and the Young Investigator Award for Contributions in Information Fusion were given this year.

The 2021 ISIF Awards Committee was chaired by Dr. Dale Blair and included Dr. Craig Agate, Prof. Yaakov Bar-Shalom, Dr. Chee-Yee Chong, Prof. Paulo Costa, and Dr. Larry Stone. This committee represents a highly accomplished and experienced group of researchers who span the breadth of scientific areas of study that are most prominent in the ISIF community. All awards are presented at the awards banquet at the International Conference on Information Fusion. Additional details of the award and selection processes are available at www.isif.org.

YAAKOV BAR-SHALOM AWARD FOR A LIFETIME OF EXCELLENCE IN INFORMATION FUSION

The premier ISIF award is the ISIF Yaakov Bar-Shalom Award for a Lifetime of Excellence in Information Fusion. This award is given for a lifetime of contributions to information fusion. It was first given in 2015 and subsequently named in 2016 for the first recipient, Yaakov Bar-Shalom, whose career began in the pre-internet days of punched cards. The ISIF Yaakov Bar-Shalom Award recognizes a researcher or engineer for outstanding contributions to the field of information fusion throughout his or her career. Contributions include technical advances, technical vision and leadership, education and mentoring, novel applications of information fusion and associated engineering achievements, and service to ISIF.

Ed Waltz is selected as the recipient of the 2021 ISIF Yaakov Bar-Shalom Award for a Lifetime of Excellence in Information Fusion. Mr. Waltz's contributions to the development and application of data fusion technology to defense and intelligence and his thoughtful leadership in the field are the basis for his selection of the award. Dr. Jim Scrofani of the Naval Postgraduate School nominated and endorsed Mr. Waltz for this honor.

2021 recipient Ed Waltz.

Mr. Waltz is a Professor of Practice in Intelligence at the Naval Postgraduate School and an Adjunct Professor of Intelligence at the Patrick Henry College in Purcellville, Virginia, USA. From 2013–2018, he was Chief of the Advanced Concepts Division, US National Reconnaissance Office, where he led research in "intelligence process research focused on automating intelligence collection and data integration" (2016). He is a recipient of the US Department of Defense's Joe Mignona Data Fusion Award (2004) and received the National Intelligence Meritorious Unit Citation for "implementing an automated, problem-centric, integrated intelligence architecture" (2015).

ISIF YOUNG INVESTIGATOR AWARD

The ISIF Young Investigator Award recognizes a young ISIF member for outstanding contributions in the field. The goals of the ISIF in granting this award are to encourage individual effort and to foster increased participation by younger researchers and engineers. This ISIF award consists of a commemorative recognition plaque and travel grant to receive the award.

Florian Meyer is the recipient of the 2021 ISIF Award for Young Investigator. Several nominations were submitted for the 2021 award, including the nomination by Dr. Stefano Coraluppi of Prof. Florian Meyer.

2021 recipient Florian Meyer.

Prof. Meyer's publication record and his contributions to graph-based localization and tracking are the basis for the award. Prof. Meyer received the Dipl.-Ing. (M.Sc.) and Ph.D. degrees (with highest honors) in electrical engineering from TU Wien, Vienna, Austria in 2011 and 2015, respectively. He is an Assistant Professor with the University of California San Diego, La Jolla, CA, jointly between the Scripps Institution of Oceanography and the Electrical and Computer Engineering Department. From 2017 to 2019, he was a Postdoctoral Fellow and Associate with Laboratory for Information & Decision Systems at Massachusetts Institute of Technology, Cambridge, MA, and from 2016 to 2017, he was a Research Scientist with NATO Centre for Maritime Research and Experimentation, La Spezia, Italy. Dr. Meyer is the recipient of an NSF Career Award. He is an Associate Editor for the *IEEE Transactions on Aerospace and Electronic Systems* and the *ISIF Journal of Advances in Information Fusion*. Dr. Meyer was a keynote speaker at the IEEE Aerospace Conference in 2020.

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FUSION Conference Awards

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FUSION 2021 BEST PAPER AWARDS

The 24th International Conference on Information Fusion (FUSION 2021) was held in hybrid mode (virtual and in person) from November 1–4, 2021. FUSION is the flagship event of the International Society of Information Fusion (ISIF), and the conference is well-established as the premier forum to present and discuss research progress and initiatives in the information fusion areas. There were attendees from around the world, with active participation from industry, government, and academia. The overview of the conference is included in this *Perspectives* issue (see p. 32).

Since its inception, ISIF has promoted a high-quality technical program at each annual FUSION conference. One way to encourage this excellence is to promote the Paper Awards program. Accordingly, each year the conference includes recognition of the best regular papers and the best student papers. Student papers are those for which the lead author is a full-time graduate (or undergraduate) student at an accredited university. As mandated by the ISIF Board of Directors, the best paper receives the Jean Pierre Le Cadre Award. The best student paper receives the Tammy L. Blair Award. These awards honor the efforts and commitment of both Jean-Pierre and Tammy to the international fusion community over many years.

The FUSION 2021 Awards Co-Chairs were Wolfgang Koch, Nageswara Rao, and Pramod Varshney. They began the selection process by examining the reviews of two short lists of papers provided by the Organizing Team of Pieter de Villiers, Alta de Waal, and Fredrik Gustafsson. The short lists consisted of 19 and 14 papers chosen from 58 and 88 candidate papers under the General and Student categories, respectively. To avoid the possibility of conflicts of interest, all papers co-authored by FUSION 2021 Organizing Team, Technical and Program Committee members, and Awards Committee members were excluded from further consideration. Reviews and quantitative scoring of these papers were conducted by Awards Co-Chairs, leading to a set of six regular and six student papers for further analysis. The Awards Co-Chairs formed the Awards Committee consisting of Stefano Coraluppi, Henry Leung, Mahendra Mallick, Ruixin Niu, Xiaojing Shen, Lauro Snidaro, and Jason Williams. All seven committee members separately ranked both sets of six regular and six student papers. No committee members were co-authors on any papers that they evaluated, and no conflicts of interest were identified. The sum of scores led to overall rankings that were ratified by the Awards Co-Chairs.

JEAN PIERRE LE CADRE AWARD

The best regular papers were the following:

- Best Paper: Ossi Kaltiokallio, Yu Ge, Jukka Talvitie, Henk Wymeersch, and Mikko Valkama, "mmWave Simultaneous Localization and Mapping Using a Computationally Efficient EK-PHD Filter"
- First Runner-Up: Angel Garcia-Fernandez, Marcel Hernandez, and Simon Maskell, "An Analysis on Metric-Driven Multi-Target Sensor Management: GOSPA versus OSPA"
- Second Runner-Up: Florian Meyer and Kay L. Gemba, "Acoustic Source Localization in Shallow Water: A Probabilistic Focalization Approach"

BEST PAPER (JEAN PIERRE LE CADRE AWARD)

Ossi Kaltiokallio, Yu Ge, Jukka Talvitie, Henk Wymeersch, and Mikko Valkama, "mmWave Simultaneous Localization and Mapping Using a Computationally Efficient EK-PHD Filter"

Abstract—Future cellular networks that utilize millimeter wave signals provide new opportunities in positioning and situational awareness. Large bandwidths combined with large antenna arrays provide unparalleled delay and angle resolution, allowing high accuracy localization but also building up a map of the environment. Even the most basic filter intended for simultaneous localization and mapping exhibits high computational overhead since the methods rely on sigma point or particle-based approximations. In this paper, a first order Taylor series-based Gaussian approximation of the filtering distribution is used, and it is demonstrated that the developed extended Kalman probability hypothesis density filter is computationally very efficient. In addition, the results imply that efficiency does not come with the expense of estimation accuracy since the method nearly achieves the position error bound.

TAMMY L. BLAIR AWARD

The best student papers were the following:

- Best Paper Award: Juliano Pinto, Georg Hess, William Ljungbergh, Yuxuan Xia, Lennart Svensson, and Henk Wymeersch, “Next Generation Multitarget Trackers: Random Finite Set Methods vs Transformer-based Deep Learning”
- First Runner-Up: Keith LeGrand, Pingping Zhu, and Silvia Ferrari, “A Random Finite Set Sensor Control Approach for Vision-Based Multi-Object Search-While-Tracking”
- Second Runner-Up: Thore Gerlach, Folker Hoffmann, and Alexander Charlish, “Policy Rollout Action Selection with Knowledge Gradient for Sensor Path Planning”

BEST STUDENT PAPER (TAMMY L. BLAIR AWARD)

Juliano Pinto, Georg Hess, William Ljungbergh, Yuxuan Xia, Lennart Svensson, and Henk Wymeersch, “Next Generation Multitarget Trackers: Random Finite Set Methods vs Transformer-based Deep Learning”

Abstract—Multitarget Tracking (MTT) is the problem of tracking the states of an unknown number of objects using noisy measurements, with important applications to autonomous driving, surveillance, robotics, and others. In the model-based Bayesian setting, there are conjugate priors that enable us to express the multi-object posterior in closed form, which could theoretically provide Bayes-optimal estimates. However, the posterior involves a super-exponential growth of the number of hypotheses over time, forcing state-of-the-art methods to resort to approximations for remaining tractable, which can impact their performance in complex scenarios. Model-free methods based on deep-learning provide an attractive alternative, as they can, in principle, learn the optimal filter from data, but to the best of our knowledge were never compared to current state-of-the-art Bayesian filters, specifically not in contexts where accurate models are available. In this paper, we propose a high-performing, deep-learning method for MTT based on the Transformer architecture and compare it to two state-of-the-art Bayesian filters, in a setting where we assume the correct model is provided. Although this gives an edge to the model-based filters, it also allows us to generate unlimited training data. We show that the proposed model outperforms state-of-the-art Bayesian filters in complex scenarios, while matching their performance in simpler cases, which validates the applicability of deep-learning also in the model-based regime. The code for all our implementations is made available at https://github.com/JulianoLagana/MT3.

The authors of these papers were recognized during FUSION 2021. Nageswara Rao announced the winners and award certificates were presented by General Co-Chair Pieter de Villiers. The selection process to decide FUSION paper awards is an important stage that complements the larger paper-review process. The awards selection is conducted with great thoroughness, identifying research of significant value that is deserving of the attention of fusion researchers and practitioners. On behalf of ISIF, congratulations to the authors of all six papers for their hard work and impressive achievement.

ISIF Working Groups Report

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UPDATES ON WORKING GROUPS

International Society of Information Fusion (ISIF) sponsors working groups by providing recognition, status, and support. The support includes a meeting place during the FUSION Conference and related website links. It can also include support for virtual meetings. The working groups bring together researchers who share a common interest. For more information on working groups, or for submitting a proposal for a new working group, please see the ISIF website: https://isif.org/working-groups/isif-working-groups, or contact Darin Dunham, Vice President Working Groups (dunhamdt@gmail.com).

Currently, there are two active working groups sponsored by ISIF. Here is a quick summary of their focus and activities.

STONE SOUP

Stone Soup is supported via ISIF's Open-Source Tracking and Estimation Working Group (OSTEWG) as well as a NATO Exploratory Team activity (SET-ET-124) and now has a digital object identifier (DOI):10.5281/zenodo.4663993. The group has continued to grow and develop over the last year or two and has a repository (https://github.com/dstl/Stone-Soup) that includes, for example, a vectorised implementation of a particle filter; multi-frame assignment; square-root and iterated Kalman Filters; particle flow implementations, and tree-based data structures for very efficient gating. Current developments include a focus on development of user interfaces, further enhancing the set of state-of-the-art algorithms that Stone Soup implements, and on configuring Stone Soup to operate effectively in sensor management contexts. New contributors wanting to integrate their algorithmic advances into an increasingly mature open-source library and/or compare their new algorithms with ever-more sophisticated pre-existing baselines are very welcome. Similarly, users wanting a taste of Stone Soup's algorithmic gastronomy should get in touch (via https://isif-ostewg.org/); highlight barriers to use as "issues" (via https://github.com/dstl/Stone-Soup/issues); or initiate or engage in discussions (via https://github.com/dstl/Stone-Soup/discussions). Help us to enable Stone Soup to help you!

ETUR WORKING GROUP ACTIVITIES

The Evaluation of Techniques for Uncertainty Representation Working Group (ETURWG) is an official activity of the ISIF with the products posted at https://eturwg.c4i.gmu.edu/. The ETURWG is going on 10 years of collaboration, continuing to refine, update, clarify, and implement the Uncertainty Representation and Reasoning Evaluation Framework (URREF) ontology. On average, 15 people participate at the bi-weekly meetings. The ETURWG activities include developing a UR-REF tutorial, incorporating Artificial Intelligence and Machine Learning (AI/ML), and defining metrics.

The ETURWG continues to explore new topics in data and information fusion processing, reasoning, and decision making with the focus on uncertainty analysis. The URREF ontology semantically captures the many elements for deploying information fusion systems, while at the same time, explores metrics of analysis, use cases, and philosophical elements of the community. All ISIF members are welcome to join the discussions and to propose future topics aligned with the ETURWG interests.

2022 IEEE INTERNATIONAL CONFERENCE ON MULTISENSOR FUSION AND INTEGRATION

We are happy to announce that the 2022 IEEE International Conference on Multisensor Fusion and Integration will be held at the Cranfield University in the United Kingdom on the 20-22 September 2022. Cranfield University is a British postgraduate public research university specialising in science, engineering, design, technology and management. It is one of the UK's leading engineering universities and has a range of facilities including the Multi-user environment for autonomous vehicles, the aerospace autonomy laboratory, the intelligent mobility engineering centre, and many more.

The main theme for this conference is `Taking Multi-Sensor Fusion to the Next Level: From Theory to Applications'. We are looking forward to a full program covering the key topics of sensors, theory, algorithms, applications and performance assessment. Full details and up to date information can be found on the conference website www.mfi2022.com.

Call for Papers: *JAIF* Special Issue on Graph-Based Localization and Tracking

Localization and tracking are increasingly important capabilities in applications including autonomous navigation, applied ocean sciences, asset tracking, future communication networks, and the internet of things. These applications pose new theoretical and methodological challenges due to the use of heterogeneous sensors and the corresponding need for data fusion, the implementation of collaborative and decentralized modes of operation, and the support of new inexpensive and low-power sensing devices. In particular, processing measurements provided by inexpensive devices is often complicated by uncertainties beyond Gaussian noise, like missed detections and clutter, an uncertain origin of measurements, and an unknown and time-varying number of objects to be localized or tracked.

Methodologically, these challenges can be well addressed by inference that leverages graphical models. The graph-based inference approach has important advantages regarding performance, scalability, versatility, and flexibility of implementation. It provides a powerful theoretical framework and a rich set of tools for modeling and exploiting the statistical structure of an inference problem. An inherent advantage of graph-based inference is that it can provide scalable solutions to high-dimensional problems. It also introduces lucidity and modularity into algorithm design, since different functional units of the overall problem appear as distinct parts in the graph. Due to these desirable properties, new graph-based modeling and inference techniques are advancing the field of localization and tracking. The special issue will demonstrate the potential of graph-based inference for localization and tracking by presenting several concrete examples where this approach has been successfully applied. Featured papers address both theoretical and application-oriented aspects, including:

- Embedded particle flow
- Scalable data association
- Geoacoustic inversion
- Maritime situational awareness
- Simultaneous localization and mapping
- Autonomous driving
- Estimation of spatial fields
- Indoor localization
- Multiobject detection and tracking

The special issue is tentatively scheduled for June 2023. Extensions of good conference papers from FUSION 2022 can be recommended for this special issue.

INTERNATIONAL SOCIETY OF INFORMATION FUSION

Guest Editors:

Domenico Gaglione (CMRE), domenico.gaglione@cmre.nato.int
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Jason L. Williams (Commonwealth Scientific and Ind. Res. Org.), jason.williams@data61.csiro.au
Florian Meyer (University of California San Diego), flmeyer@ucsd.edu

Timeline:

1 Sep 2022 – submission deadline
1 Nov 2022 – 1st decision sent to authors
1 Jan 2023 – 1st revision deadline
15 Feb 2023 – 2nd decision sent to authors
1 Apr 2023 – 2nd revision deadline
1 May 2023 – final decision sent to authors
1 Jun 2023 – final manuscript deadline
Jun 2023 – publication JAIF Vol. 18(1)

Submissions: Visit http://isif.org/journals/all for general information on *Journal of Advances in Information Fusion* and https://jaif.msubmit.net for manuscript submission.

FUSION 2021 Report

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REPORT ON THE 24TH INTERNATIONAL CONFERENCE ON INFORMATION FUSION

The International Society of Information Fusion (ISIF) hosted its 24th International Conference on Information Fusion at the Sun City Conference Centre in Rustenburg, South Africa from 1–4 November 2021.

The South African Local Organising Committee (LOC), in consideration of the effects of the COVID-19 pandemic and many international travel restrictions, hosted a "hybrid" conference. Attendees were given the option of attending online or onsite and were given the opportunity to change these options at short notice.

The conference was attended by 214 people, of whom a quarter attended onsite. The event featured 10 tutorials, a free collaborative workshop, 146 papers, and three keynote speakers, viewed by attendees from 30 countries. The tutorials were followed by the three-day technical programme. The programme included general and special sessions that were convened in five break-out rooms.

The social programme included an informal welcome dinner, a game drive, an outdoor Boma (BBQ) dinner, a fun-run, and gala dinner that were all hosted at the Sun City Conference Centre and the Pilanesberg National Park.

Coordinating four days of intense onsite activities and remote, real-time participation by means of Slack and Zoom was an immense logistical undertaking.

KEYNOTE SPEAKERS

We wish to thank our keynote speakers for their inspiring words in the run-up to each conference day's proceedings. They brought to conference attendees an excellent addition of technical competence, experience, and passion for information fusion, in perspectives ranging from local and international academia and industry. This year's keynote speakers were:

- Prof. Russ Taylor, the Square Kilometre Array (SKA) Research Chair in Radio Astronomy from the University of Cape Town and the University of the Western Cape, on "The SKA: Big Telescope, Big Science, Big Data"
- Prof. Simon Maskell, of the University of Liverpool, on "Particles 2.0: Non-linear Non-Gaussian Inference for 2021"
- Dr. Edward Tunstel, CTO of Motiv Space Systems, Inc., on "From Behavior Fusion to Memetics for Next-Level Robotic Intelligence"

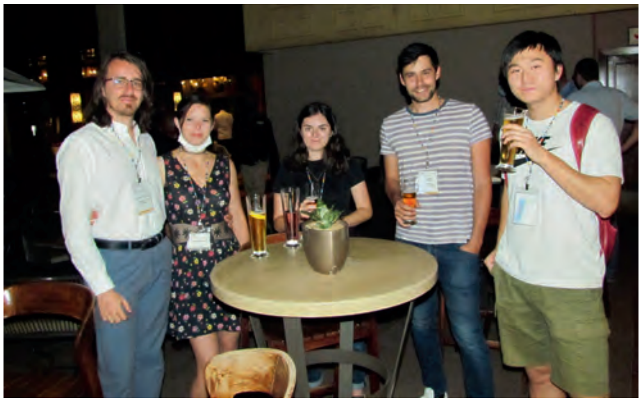
TECHNICAL PROGRAMME

Regarding the technical aspects of the conference, an open call for papers was circulated, and conditions amid COVID lockdowns the world over were challenging again. In spite of this, we were still able to attract a total of 211 paper submissions, of which 146 were accepted. This equates to an acceptance rate of 69%. (This is compared to 167 papers accepted out of 230 paper submissions in 2020, a 73% acceptance rate.) All presented papers appeared in the published proceedings that are accessible through IEEE Xplore. The conference proceedings publication was also Scopus indexed and can be downloaded from the conference website at https://www.fusion2021.co.za/epc/ (password protected).

A strict single-blind peer-review process on the full paper submission was applied with three or more reviewers from the relevant discipline per paper. We would particularly like to thank the Technical Chairs for coordinating the review process (the same team as in 2020), especially Lyudmila Mihaylova, Paulo Costa, Anne-Laure Jousselme, Zhansheng Duan, and Simon Godsill, the Program Chairs Erik Blasch and Kathryn Laskey, as well as the team of hundreds of volunteer reviewers drawn from across the international fusion community. Without their hard work and efficiency, we would not have been able to manage the review process and compile the programme. We thank Special Session Chairs Roy Streit and Joel Dabrowski, who assisted with the recruitment and selection of special sessions. Furthermore, we wish to thank the many colleagues from around the world who have helped to attract high-quality papers. Special Session papers were subject to the same review process as regular papers. A complete list of all special sessions can be found on the conference website at https://www.fusion2021.co.za/.

SOCIAL ACTIVITIES

In keeping with tradition, FUSION 2021 was hosted at a superb conference venue, the Sun City Convention Centre. Sun City is situated a mere 200 km from Johannesburg and borders on the Pilanesberg National Park. The Park covers 55,000 hectares and is the fourth largest National Park in Southern Africa. It is home to, among others, the big five animals of Af-



FUSION 2021 students at the informal welcome dinner, with drinks at the Luma Lounge and Deck.

Snapshot of the Gala Banquet, including Prof. Fredrik Gustafsson, Dr. Claire Laudy, Dr. Alta de Waal, Dr. Kathryn Laskey, Dr. Ali Raz, and Mrs. Hina Khalid.

Mr. Cedric du Mouza and Ms. Camelia Constantin, with their daughters.

rica. The Park, furthermore, is perched on the eroded vestiges of an alkaline volcanic crater, one of only three such craters in the world. Sun City also lies within this crater. The FUSION 2021 conference logo symbolised this crater in ancient rock art drawings style, of which many can be found in abundance in Southern Africa.

The FUSION 2021 LOC packed the social programme with the very best that was offered by Sun City and its surrounds. On Monday, 1 November, guests were hosted to an informal welcome dinner and drinks at the Luma Lounge and Deck of the Cascades Hotel, overlooking the lush green gardens of Sun City and the hills of the Pilanesberg National Park in the distance.

On Tuesday, 2 November, the agenda was scheduled to end earlier than usual to make provision for a three-hour Safari Game Drive in the Pilanesberg National Park in search of the big-five. Attendees were not disappointed as they spotted lion, leopard, buffalo, elephants, rhino, giraffes, and many antelope during the game drive. Following the game drive, attendees were treated to an outdoor Boma "Braai" (BBQ) dinner, including traditional South African delicacies under a gorgeously clear African night sky. Many stories were shared of the abundance of animals that had been "spotted" on the game drive.

At 06:30 on Wednesday, 3 November, many of the attendees arrived to participate in the traditional 5 km Fun Run. The run followed a path along the lush Gary Player Golf Course. (Some of the participants may have completed the course faster than usual as a leopard had been spotted on this course the previous evening.) The winner of the 2021 Fun Run was Yunpeng Li with a time of 24:51, followed by Jonas Åsnes Sagild and Mauritz Kloppers.

The FUSION 2021 Gala Dinner took place in the Sun City Conference Centre Ballroom. Before dinner was served, an awards ceremony recognized some of ISIF's greatest contributors. The night's main attraction was a musical and theatre performance by traditional Gumboot Dancers. The evening was thoroughly enjoyed by all!

ORGANISATION

"This was the first onsite ISIF conference held on the African continent. The South African LOC compiled a programme, which included some of the premier South African experiences that could be accommodated in the four-day agenda: a five-star conference venue, a high standard of hospitality and an exceptional wildlife experience," said General Co-Chair, Prof. Pieter de Villiers. The conference was originally scheduled to take place in July 2021, but was postponed to November 2021, with the hope of enabling ISIF members to attend the conference onsite.

> ***"This was by far the most enjoyable conference I have ever attended. I think we might have a problem leaving the children at home when next we attend a conference, as they are under the impression that all conferences include this many exciting social events..."***
>
> *Prof. Cedric du Mouza, Associate Professor, CNAM, France*

FUSION 2021 attendees on the Game Drive.

Photo by Pieter de Villiers.

Photo by Keith LeGrand.

Photo by Keith LeGrand.

Photo by Keith LeGrand.

FUSION 2021 attendees on the Game Drive.

BUILDING ON PAST EXPERIENCES

In 2020, the South African LOC spent many hours considering and implementing solutions for the best possible online conference experience. All of us have attended past FUSION conferences, and our aim was to offer nothing less than an event of technical excellence.

In 2021, we decided to combine the finest of both conference formats—as we were able to offer an onsite and online attendance option—which equated to double the effort required to host either format. The success of this event can be attributed to the continued support of a vibrant information community.

We wish to thank all of our committee members and other volunteers for their selfless contributions in time and expertise, and the assistance from past organisers whose input was truly invaluable to a successful FUSION 2021. We were thrilled to be able to host FUSION 2021 as a "hybrid" event as nothing could have replaced the social aspects of the on-site conference in combination with excellent online contributions.

CALL FOR PAPERS
14th 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

Towards Using Large-Scale Sequential Monte Carlo to Get Big Information Out of Small Data by Simon Maskell

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

- Proof of student status required for student registration
- One registration covers one paper only

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/sdf2022.

Important Dates

31 Aug 2022	Submission of full draft papers
15 Sept 2022	Notification of acceptance
29 Sept 2022	Submission of the final version
12 Oct 2022	Start of SDF 2022

Fees

[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
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Organisation

Executive Chairs: **Wolfgang Koch**, Fraunhofer FKIE and Univ of Bonn, w.koch@ieee.org; **Peter Willett**, Univ. of Connecticut, p.willett@ieee.org
Technical Program Chair: **Felix Govaers**, Fraunhofer FKIE

Technical Program Committee

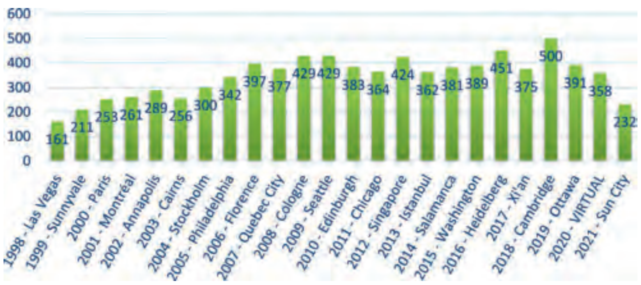
Marcus BAUM, Univ of Gottingen, GER; Jurgen BESTLE, HENSOLDT, GER; Christian BRANDLHUBER, 21strategies, GER; Chee CHONG, Consultant, CA, USA; Stefano CORALUPPI, STR, MA, USA; Armin B CREMERS, Univ of Bonn, GER; Daniel CREMERS, Technical Univ Munich, GER; Klaus DIETMAYER, Univ of Ulm, GER; Darin DUNHAM, Lockheed Martin, USA; Bharanidhar DURAISAMY, Daimler, GER; Murat EFE, Ankara Univ, TK; Frank EHLERS, FWG, GER; Dietrich FRANKEN, Airbus Defence and Space, GER; Jesus GARCIA, Univ Carlos III, Madrid, ES; Fredrik GUSTAFSSON, Linkoping Univ, SW; Uwe D. HANEBECK, Karlsruhe Institute of Technology KIT, GER; Bernhard KRACH, Airbus, GER; Joerg KUSHAUER, Diehl BGT Defence, GER; Henry LEUNG, Univ of Calgary, CA; Lyudmila MIHAYLOVA, Univ of Sheffield, UK; Gee Wah NG, DSO, SGP; Umut ORGUNER, Univ of Ankara, TR; Johannes REUTER, Univ of Applied Sciences Konstanz, GER: Stefan REUTER, Robert Bosch GmbH, GER; Lauro SNIDARO, Univ of Udine,IT; Klauss-Dieter SOMMER, Univ of Ilmenau, GER; Roy L. STREIT, Metron Inc., USA; Jorn THIELECKE, Univ Erlangen, GER; Reiner THOMA, Technical Univ Ilmenau, GER; Martin ULMKE, Fraunhofer FKIE, GER

25 Years of FUSION Conferences: Collection of Memories

INTRODUCTION

CHEE-YEE CHONG, ISIF TREASURER, 1998–2022

FUSION 1998 was held in Las Vegas, NV, a city known for its casinos. It was an appropriate location because without an established community in information fusion, organizing the first international conference was a gamble. As it turned out, FUSION 1998 was not a financial success. However, the conference provided an opportunity for information fusion researchers from all over the world to meet and share their research. The need to continue the conference was recognized by a group of attendees, who formed the International Society of Information Fusion (ISIF) in September 1998 to be the primary sponsor of future conferences.



FUSION conference attendance.

FUSION 2022 is the 25th International Conference on Information Fusion. Since 1998, the conference has been held annually with no interruption in North America (10), Europe (10), Asia (2), Australia (1), and Africa (1) and virtually (1). As the only annual international conference focused on information fusion, it has attracted a core of regular international attendees from academia and industry, along with students who are the future of the fusion community. Many research collaborations and projects have resulted from conversations during coffee breaks and at social events. The technical program presents the latest advances in information fusion research and trends, e.g., large numbers of machine learning papers in recent years. The conference proceedings, available on the ISIF website and Institute of Electrical and Electronics Engineers (IEEE) Xplore, are arguably the best sources of publications on information fusion research.

We have invited the organizers of the past FUSION conferences to share their memories in this paper. They share how FUSION 1998 led to the formation of ISIF, how Paris was chosen to be the first location outside North America, how ISIF built up its financial reserve, that coronavirus disease 2019 (COVID-19) is not the first pandemic for the FUSION conferences, and how one organizing committee had to organize two conferences. Although reports of some conferences have been published previously, e.g., FUSION 1998 and FUSION 1999 in the first issue of *Perspectives on Information Fusion* [1], this paper provides additional memories of the organizers.

25 FUSION conferences held on five continents.

FUSION 1998, LAS VEGAS, NV

X. RONG LI, CHAIR, STEERING COMMITTEE

I will add more background to the report on FUSION 1998 that appeared in the first issue of the *Perspectives* magazine [1]. FUSION 1998 was the first of the FUSION conferences. In summer 1997, Dongping (Daniel) Zhu and Hamid Arabnia met at the annual International Conference on Parallel and Distributed Processing Techniques and Applications (PDPTA) in Las Vegas, NV. With a Ph.D. from Virginia Tech in neurofuzzy and expert systems in 1993, Daniel was an entrepreneur who just started Zaptron Systems, a small company in Silicon Valley. Hamid was associate professor of computer science at the University of Georgia and had a small company, Computer Science Research, Education, and Application (CSREA), which ran a dozen or so professional conferences each year, many of which were in Las Vegas. They were both interested in starting a new conference. Their interaction during PDPTA'97 led to the idea of having such a conference in data fusion (Daniel suggested and Hamid agreed). Since neither of them were active in the data fusion area, they sought someone in this area to help. Of these two people, Daniel was the more energetic and proactive then. He searched the Internet and found me. I was told the above origin by both of them at FUSION 1998.

Dongping (Daniel) Zhu, Yaakov Bar-Shalom, and Rong Li.

In early fall 1997, Daniel called me and we had a long talk. He said he contacted me because he knew I had many publications, including books, in the target tracking and data fusion area. He proposed having a new conference on data fusion and appointed himself as the general chair. He invited me to serve as the steering committee chair. I hesitated at first for several reasons. Earlier, Neil Gordon told me briefly that someone was proposing a conference on fusion, and I didn't think it was a good idea—I've always thought that there are in general too many conferences. Even worse, Daniel was not really in the traditional data fusion area, so it was neither proper nor likely for him to succeed in starting such a conference. But after our conversation, I thought more about it and concluded that such a conference was probably a good idea for the fusion research community. Most importantly, we could offer this opportunity and let the community decide. So I decided to promote it actively and accepted Daniel's invitation.

Shozo Mori, Chee-Yee Chong, and Jim Llinas.

Then I contacted, mostly by phone, about three dozen of well-known researchers in the fusion area. The idea of having such a conference was well received by most of them. I then formed the steering committee with 18 of those researchers who agreed to serve, including notably (and alphabetically) Henk Blom, Chee-Yee Chong, Oliver Drummond, Alfonso Farina, Ivan Kadar, Rudolf Kruse, Jim Llinas, Shozo Mori, and Pramod Varshney. I also arranged for Prof. Yaakov Bar-Shalom at the University of Connecticut, a towering figure in tracking and fusion, to deliver a keynote speech. In the hope of having a broad scope for the conference, Daniel invited another keynote speaker, Colin Johnson, an editor of *Electrical Engineering Times*, who was not in the fusion area.

Daniel got some other people on board and formed the apparent organizing team, but the de facto organizing team was only the three of us—I don't think anyone else really did anything significant for the organization of FUSION 1998. Other than promoting the conference and getting people involved, Daniel also maintained the conference website. Hamid didn't get anybody involved, but his CSREA handled all logistics, including the conference site (Monte Carlo Resort and Casino, Las Vegas), paper processing (acceptance and rejection), technical program setup, and conference registration. It was efficient because CSREA held a parallel conference, the International Conference on Imaging Science, Systems, and Technology. I met Chee-Yee for the first time at FUSION 1998, although we were on the phone multiple times before the conference. His first comment when we met was that three brave young guys had started the FUSION conference and made an interesting history. Yes, indeed, we are all indebted to Daniel for this.

Dr. Rabinder Madan, a program director at the Office of Naval Research (ONR), had been supporting fusion research, including me, for some years. So I called Rabi for financial support of the conference. After some negotiation he finally agreed to $8,000, mainly for student support, and he would serve as general cochair. I submitted a proposal to ONR and received the money through my school—the University of New Orleans (UNO). I also submitted a proposal to Dr. William Sander of the Army Research Office (ARO) and received $9,999 through UNO to support FUSION 1998. Through his connections, Daniel received some financial support from the Army Night Vision and Electronic Sensors Directorate. As far as I remember, these were the only financial supporters for FUSION 1998. In the end, according to the brief financial report Hamid sent me in April 1999, FUSION 1998 had a deficit of $8,887, which was covered by the surplus of PDPTA'98. But this information was not necessarily reliable. Later, we learned that Hamid's CSREA was a for-profit organization. That's why we decided to move away from CSREA for future conferences and form a fusion society to be the sponsor.

Rong Li, Jean Dezert, Vincent Nimier, and Alain Appriou.

According to the documents I still have, FUSION 1998 was truly international. It had a total of 161 attendees from 24 countries or regions, in which 45% were from United States. Papers were submitted from 34 countries or regions (fewer than half were from United States); 166 of them were accepted (159 regular papers and 7 short papers), and 144 of the accepted papers were presented at the conference. The conference proceedings included 136 papers in 29 sessions. This was indeed good success for a first conference. According to Hamid, FUSION 1998's acceptance rate was low (something around 40%), which surprised me a lot and is still hard to believe. He said that's because there were many low-quality submissions from third-world countries (e.g., countries in the Middle East had more than 30 submissions, which was never repeated in later FUSION conferences, to my knowledge).

Around the time of FUSION 1998 and at the conference, several activities were undertaken to explore the possibility of forming a fusion society to sponsor future FUSION conferences. I prepared and distributed to conference attendees and via email a questionnaire that included a bunch of what we thought were important questions. We received several dozen written responses. At the conference, in addition to many informal discussions, we had a couple of more formal occasions to discuss these responses. I also set up a website, Infofusion.org, to solicit input on a fusion society, as well as fusion conferences, and to disseminate useful information on fusion research. The responses were mostly positive for future fusion conferences and the society. Then, the formation of ISIF and the annual International Conference on Information Fusion took off [1].

FUSION 1999, SUNNYVALE, CA

X. RONG LI, GENERAL VICE CHAIR

During FUSION 1998, I tried to form committees to make the preparation of FUSION 1999 more formal and systematic for the benefit of the fusion community, but Dongping (Daniel) Zhu resisted, mainly because he had his own interest as an entrepreneur. Right after FUSION 1998, he appointed himself again as the general chair for FUSION 1999 and announced it on the FUSION 1999 website, which he maintained. I was not happy with this but eventually agreed to serve as general vice chair, given the situation. Then, I was eager to make the technical program rigorous. At the suggestion of some people, I called Prof. Pramod Varshney of Syracuse University and invited him to serve as the program chair, as well as recommending Prof. Peter Willett of University of Connecticut as his deputy. In his always pleasant and gentle manner, Pramod was happy to accept the invitation, along with Peter. Mainly due to their good efforts and rich experience, the technical program, including a rigorous review process, was a great success and set a good example for later years to follow. I was happy about the outcome. However, since Hamid Arabnia's CSREA was no longer involved with FUSION 1999, Daniel did a lot of work beyond website maintenance, including many time-consuming logistics jobs such as local arrangement. This justified his choosing of the conference to be in Sunnyvale, CA, in Silicon Valley, where his company Zaptron was located.

Because of my research background, I knew more fusion experts with a defense and/or aerospace background, as reflected in the steering committee's makeup of FUSION 1998. For 1999, I tried to broaden the scope of the FUSION conference, especially on the non–military application side such as robotics, and get more fusion experts on that side involved. Toward this end, I invited Prof. Ren Luo of Taiwan's National Chung Cheng University to give a keynote speech at FUSION 1999. Ren initiated the IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI) in 1994 when he was in the United States and had dominated MFI ever since.

My invitation had a more specific purpose: we took this opportunity and tried in vain to persuade Ren to consider some type of collaboration or coordination between the MFI and the FUSION conferences. But he clearly showed no interest in such potential. MFI and FUSION have been independent conferences ever since, with little coordination. However, Prof. Uwe Hanebeck of the Karlsruhe Institute of Technology, Germany, was general chair for both the MFI and the FUSION conferences in 2016. I really hope Uwe and other likeminded people can make a better effort to connect MFI and FUSION conferences.

CHEE-YEE CHONG, FINANCE CHAIR

I became the FUSION finance chair because I was the ISIF treasurer. As an outsider to the fusion community, Daniel wanted the conference finances to be transparent to ISIF. It also helped that we both lived close to the conference hotel in Sunnyvale, so we could meet frequently. Since ISIF was a newly formed society with no money in the bank, Daniel signed the contract on behalf of FUSION 1999. In fact, he paid the fees associated with the incorporation of ISIF. This was a financial risk to Daniel, but he was confident that his investment would pay off given the attendance of FUSION 1998.

The eventual financial success of FUSION 1999 was the result of excellent marketing to attract participation, as captured by a screenshot of the FUSION 1999 website, which included four other fusion-related meetings in 1999—the National Symposium on Sensor and Data Fusion (NSSDF-99), the National Aeronautics and Space Administration (NASA) Data Fusion–Data Mining Workshop, MFI 1999, and EuroFusion99. The key people from these conferences were invited to join the executive committee and/or give plenary talks: Frank White from NSSDF, Ken Ford from NASA, Luo from MFI, and Mark Bedworth from EuroFusion99. The NASA Workshop held immediately after FUSION 1999 was free to FUSION 1999 attendees and helped to boost attendance. NASA also provided funding support. The executive committee included Belur Dasarathy, who was active in SPIE fusion meetings, ran a website on sensor fusion, and was the founding editor in chief for the *Information Fusion Journal.* The result was a 25% increase attendance from FUSION 1998, with 15 people from France who would go on to organize FUSION 2000 in Paris, France.

FUSION 1999 website.

Since ISIF had no reserve, Daniel would not be paid for his services if there was a loss. Thus, he performed most of the conference administration and local arrangements functions himself, including hotel negotiation, website management, proceedings publication, and registration invoices and payment. He had help from other volunteers. In addition to collecting the papers for the proceedings, Publication Chair Bob Levinson took preregistration via fax. Erik Blasch, besides contacting sponsors, spent his own time and money to make the CD-ROMs. We spent the bare minimum on social events and did not provide lunch. For the welcome reception, I monitored the hors d'oeuvre trays and ordered replenishments in real time. By maximizing revenue and minimizing expenses, FUSION 1999 had a moderate surplus after paying Daniel for his services. This surplus provided ISIF with a healthy balance in the bank.

FUSION 2000, PARIS, FRANCE

JEAN DEZERT, ORGANIZING COMMITTEE

The decision to organize the first FUSION conference in Europe, and especially in Paris, France, was made during a meeting of several founding members of ISIF, in particular Yaakov Bar-Shalom, Xiao-Rong Li, Chee-Yee Chong, and Erik Blasch at FUSION 1999 in Sunnyvale, CA. As early as 1999, the need was felt to develop and promote the tracking and fusion theme through a truly international conference that would minimize conflicts of interest among private sponsors, organizers, and researchers. With this in mind, Alain Appriou, Jean-Pierre Le Cadre, and I decided to apply to organize FUSION 2000 in Paris with all the passion of youth.

Jean-Pierre Le Cadre, Gabriel Ruchet, and Ivan Kadar.

The first challenge was to strengthen our small core, and the second one was to find solid financial sponsors ready to take the financial risk in the event of a deficit. The reputation and address books of Alain and Jean-Pierre, as well as my connection with Yaakov and Xiao Rong, helped in the first challenge. For the second one, the French National Research Council, the French Office National d'Etudes et de Recherches Aérospatiales (ONERA), and Thomson-CSF were the three sponsors for the event, covering the local organization, the printing of the proceedings, the secretarial, and the website development (Sylvain Gaultier from ONERA). The choice of the venue naturally fell to the Cité des Sciences to give scientific color to this conference.

Gala dinner on the bateaux mouches on the Seine River.

For the social event, it seemed obvious to us that the choice of a dinner and a night visit of Paris on *bateaux mouches* was the best option, which would potentially attract more foreign participants with their families to Paris for this conference. This choice was wise, and many people whom I saw again years later during the following conferences still remembered this night visit to Paris during FUSION 2000. Some even came from afar on a "honeymoon" in Paris during FUSION 2000. In 2000, powerful web development tools and social networks did not exist. Although present in universities since the 1980s, LaTeX was not yet well mastered by the majority of researchers, and we had no database of email addresses to promote the event. We built the mailing list quickly from the two small conferences, FUSION 1998 and FUSION 1999 (with mainly American participants), extended by analyzing recent articles relating to the areas covered by the conference. I spent hours, evenings and weekends, but it was worth it, because doing so brought high participation of both European and non-European researchers. The plenary speakers were Henri Prade, Philippe Smets, Dov Gabbay, and David Schum thanks to Alain's contacts. The intents behind these choices were to broaden the conference to researchers close to artificial intelligence and to try to forge links between people in defense applications (radar scientists who essentially did tracking and multisensing with probabilistic methods) and those who developed nonprobabilistic techniques for decision support in both civilian and military fields of application. I think in particular that Philippe, with his presence, his passion, and his outspokenness, had a strong impact on participants and young researchers. I still remember him. What a guy!

Philippe Smets.

One of the most striking memories during the organization concerns the edition of the paper volumes of the proceedings of the conference. ONERA's printer worked days and nights to produce cardboard boxes of volumes that were then stacked in the corridors of the basement, from floor to ceiling. They were absolutely everywhere. Unfortunately, attendees who had to travel preferred the CD-ROM, leaving us with many orphan paper copies of the proceedings. Another neophyte error was the massive sending of call-for-papers messages by email to promote the conference with a PDF file attached. Unfortunately, a too high number of messages bounced back from outdated email addresses and blew up the ONERA mail server (I won't be caught again). The organization of this conference was a very big job for me, and I lost a few pounds (which unfortunately I have since gained back).

The breakthrough of this first European conference was, I think, a change of scale and dimension, which allowed it to be established as a truly international conference. It also opened the door to alternatives to pure Bayesian approaches to tracking and fusion, allowing nonprobabilistic techniques to be maintained in the topics of the following conferences.

Jean Dezert.

It is difficult to predict the future, especially in the current context, which does not favor the development of conferences. However, face-to-face interactions are essential among researchers to establish new contacts and collaborations. I do not believe in the sustainability of purely online conferences, even if for the moment we have few choices other than compromises. Participants enjoy going to conferences, discovering new places, and chatting and socializing with their colleagues. I think it is as vital for them as it is for me. Moreover, if the conference tightens up on the basic themes (filtering and tracking only), I fear that it will end up attracting only limited audience and will lose the prestige built up over the last (almost) 3 decades. It is imperative that talented young researchers take up the torch and invest in the organization of future editions of the FUSION conference.

FUSION 2001, MONTREAL, CANADA

ELISA SHAHBAZIAN, PROGRAM COCHAIR

The fourth FUSION conference in 2001 was held in the cosmopolitan and bilingual city of Montreal, Canada, August 7–10, during a record-breaking heat wave and 35 days without rain. The chosen venue of the 30-story Hotel Delta Centre Ville was centrally located, close to historic Old Montréal and Chinatown, and only minutes away on foot from downtown. The buffet-style banquet was held in the rotating penthouse restaurant Tour de Ville, which gave the attendees a view of the city and the harbor and featured Canadian cuisine from coast to coast. The organization and sponsorship were shared by Lockheed Martin Canada (LM Canada), the Network for Computing and

Mathematical Modeling of the Centre de Recherches Mathématiques (CRM) of the Université de Montréal, the Defense Research Establishment Valcartier (now Defence Research and Development Canada–Valcartier), the Canadian Space Agency, and Mathematics of Information Technology and Complex Systems, and the conference was under technical cosponsorship of the IEEE Aerospace and Electronic Systems (AES) Society.

Yaakov Bar-Shalom, Elisa Shahbazian, and Jim Llinas.

In addition to the numerous Canadian technical joint contributions of academia, defense research, and industry, these organizations contributed in the administrative tasks synergistically, with CRM supporting the conference registration. Finally, hard-copy proceedings (the last time for ISIF) were published, including figures in color, jointly collated by LM Canada researchers and students from academia. Such collaboration ensured a low registration cost, even for 2001.

Pierre Valin.

The FUSION 2001 conference had 261 participants in attendance, seeing 146 technical contributions from 304 authors representing 19 countries. Several keynote speakers took the floor every morning of the conference, including the Canadian astronaut Bjarni Tryggvason; Guenther Palm of Ulm University, who presented an interesting robotic project of two teams of robots playing soccer; and Pierre Valin (LM Canada and technical chair). A panel discussion, posters, and booths completed the program.

FUSION 2001 Canadian committee and attendees, including Eric Ménard, Daniel Turgeon, Dale Blodgett, Jean Couture, Eric Lefèbvre, Elisa Shahbazian, Bruce McArthur, Chris Helleur, Stéphane Paradis, Jean Roy, Eloi Bossé, Claude Tremblay, Daniel Roy, Yannick Allard, Jean-François Truchon, Frédéric Lesage, Hugues Demers, Guy Michaud, and Pierre Valin.

As Erik Blasch and Pierre Valin reported, "The mood was enthusiastic and the weather as usual sunny, and hot enough to warrant short sleeves or even shorts!"

FUSION 2002, ANNAPOLIS, MD

X. RONG LI, GENERAL CHAIR

As the general chair of FUSION 2002, looking back, I am particularly proud that it made many firsts in the history of the FUSION conference.

FUSION 2002 was the first conference that made a sizable amount of profit and thus made a major contribution to ISIF's "primitive accumulation of capital." With the help of Sponsors Program Chair Nageswara Rao, I secured a record number of financial sponsors with a record amount of financial support, including various U.S. government agencies, as well as ISIF and the IEEE AES Society. In addition, various professional societies were our technical sponsors, including several societies of IEEE, the Institution of Electrical Engineers (now the Institution of Engineering and Technology [IET]), and the American Institute of Aeronautics and Astronautics.

FUSION 2002 organizing committee and attendees, including Thia Kirubarajan, Pierre Valin, Jean-Pierre Le Cadre, Kouthar Benameur, Mohammad Farooq, Jean Dezert, Mahendra Mallick, Bijoy Ghosh, Yaakov Bar-Shalom, W. Dale Blair, Xiao-Rong Li, Wolfgang Koch, Benjamin Slocomb, Erik Blasch, Shozo Mori, Chee-Yee Chong, Alexander Tartakovsky, Peter Willett, and Nageswara Rao.

To make the conference more attractive and to help ISIF grow financially, we made a self-sacrifice deal—ISIF and the IEEE AES Society would share the profit but would not take the loss if any occurred. ISIF had limited financial resources, since it was formed only in 1998, and the IEEE AES Society granted us use of its name for recognition but did not want to take the risk. As the general chair who signed all contracts, I was quite concerned about the financial risk. For example, to lower the room rates, our contract with the conference hotel specified that we would be penalized if not enough hotel rooms were booked (i.e., below a threshold) by a certain date in June. I had been nervous for a month or so because far fewer rooms than expected were booked, until the threshold was suddenly exceeded in the final couple of days. If that hadn't happened, my wife would have been quite unhappy. In the end, FUSION 2002 made a good profit of $46,000, which was quite significant at that time.

FUSION 2002 was the first FUSION conference sponsored financially by IEEE. Mainly because of Dale Blair's ground-work, it was financially sponsored by the IEEE AES Society. The success of FUSION 2002 facilitated IEEE's sponsorship in later years. Such sponsorship improves the FUSION conference's image and recognition significantly, although the international fusion community as a whole may want to maintain its independence from IEEE in many other aspects. I handled all the tedious paperwork required by IEEE for FUSION 2002. Partly based on this experience and the resultant understanding, when I was later in charge of FUSION 2017, resisting pressure from some ISIF board members, I decided not to seek financial sponsorship from IEEE for two main reasons: (a) IEEE's regulations and the Chinese government's regulations may have conflicted, which would have been a disaster for FUSION 2017, and (b) I firmly believed that FUSION 2017 would make a good profit and I would want ISIF to take all of it, rather than share with IEEE as done for FUSION 2002.

Knowing Dale's ability and energy in such activities and his close connection with the IEEE AES Society, I had been trying to get him involved in ISIF and FUSION conferences for some time. FUSION 2002 was the first year he was fully involved, as its steering chair. His contribution was so great that FUSION 2002 might be mistaken by an outsider as an educational conference of Georgia Tech (Dale's affiliation). History has proved that he has been such an important presence in ISIF and FUSION conferences ever since that it would be hard to get rid of him. In addition, partly due to Dale's contribution, I did not feel overwhelmed by organizing FUSION 2002. For example, Elisa Shahbazian, FUSION 2001's program chair, predicted that as general chair, I would personally have fewer than six papers (as in 2001) for FUSION 2002, but I found time to finish eight papers. The good experience with FUSION 2002 was a major reason I was willing to take the lead in organizing FUSION 2017. However, that time, I was totally overwhelmed because of the tremendous amount work and less experience of the organizing team, although the team worked harder than the one for FUSION 2002.

W. Dale Blair (far right) and some student attendees.

FUSION 2002 had a student paper program, with Dale as the main driving force. This started the FUSION conference's tradition of formally having a student paper program. A student paper is any paper for which a student is the principal author and primary contributor. The student paper program had the following components: The principal authors presented accepted papers in a special session so designated; travel expenses up to $500 of the principal author of each student paper were granted. In addition, conference registration fees were waived for the principal author, the principal author of each paper could choose to take a tutorial free of charge, and one paper was selected for the best student paper award, with a certificate, a $250 prize, and its principal author presenting the paper orally at a conference luncheon. More than 30 students attended FUSION 2002.

X. Rong Li.

Students are the future. To be successful, the conference should attract more students, even at the expense of financial loss for the conference.

FUSION 2002 also started the tradition to have a tutorial program. I recognized the need and asked Chun Yang of Sigtem Technology to take the lead as tutorial chair. In the end, a full array of (10) half-day tutorials in parallel sessions were given. This allowed more than 120 attendees, especially students, to learn about several disciplines or focus on one main subject. It was a great success.

FUSION 2003, CAIRNS, AUSTRALIA

ROB EVANS, GENERAL CHAIR

The sixth International Conference on Information Fusion was held in July 2003 in the Radisson Hotel in the city of Cairns in the warm tropical north of Australia. Many attendees enjoyed visiting the range of interesting sites near Cairns, including the beautiful islands of Great Barrier Reef and the vast jungle of Daintree National Park. Plenary speakers included Yaakov Bar-Shalom discussing dynamic sensor scheduling and Madhyam Srinivasan describing his work on optical flow and insect navigation. A strong lineup of seven tutorials attracted strong attendance. Overall, it was a rewarding conference, both technically and socially, for everyone.

FUSION 2003 group picture.

FUSION 2004, STOCKHOLM, SWEDEN

PER SVENSSON, GENERAL CHAIR, AND JOHAN SCHUBERT, TECHNICAL PROGRAM CHAIR

The seventh International Conference on Information Fusion was held in Stockholm, Sweden, from June 28 to July 1, 2004. The conference was sponsored by ISIF and received substantial financial and organizational support from the Swedish Defence Research Agency. In addition, we received significant financial support from Saab AB and Ericsson Microwave Systems AB. Lockheed Martin Corp., Sjöland & Thyselius AB, and the *International Journal of Information Fusion* were important contributors. The conference program contained 55 technical sessions on 26 different topics, as well as three invited paper sessions, two panel discussions, and for the first time at a FUSION conference, a best paper presentation. On the first day, we had a tutorial day with eight tutorial sessions, all taught by experts who are internationally recognized in their fields.

Stockholm City Hall.

That year, we made a concerted effort to raise of the FUSION conference to the high standard that can be expected of an international academic conference. To give more time for reviewers to perform thorough reviews and more time for authors to respond to the reviewer suggestions and improve their papers, we moved the submission deadline forward by 1 month. We promoted the conference heavily through thousands of emails and hundreds of posters sent to departments all over the world. One of the goals was to obtain submissions from the management of uncertainty (MoU) community in an attempt to bring the information fusion and the MoU communities closer. Thus, the promotion was directed to both the information fusion and the MoU communities, and we received several papers from the MoU community at that year's conference.

The conference received a record number of 279 submissions, up from 242 the prior year. A total of 171 papers were accepted, for an acceptance rate of 61.3%. The three themes of the general conference (theoretical and technical advances, algorithms and systems, and applications) received 195 submitted papers, of which 116 were accepted, for an acceptance rate of 59.5%. The seven special sessions received 84 submissions with 55 papers accepted, for a slightly higher acceptance rate of 65.5%. These rates were somewhat lower than in previous years but more in line with other high-quality academic conferences.

Jesus Garcia and Andres Soto.

The program committee consisted of 115 international experts. For the first time, at least three independent reviewers, assigned through computerized matching based on reviewing topics, reviewed each submission. In addition, 56 extra reviewers participated in the review process. All submissions to special sessions went through the same review process as other submissions. Special session organizers served as a fourth reviewer in their sessions. In total, 907 review reports were made. This review effort was more than twice that of the previous year as a result of the dedication of the members of the program committee to achieving a top-quality conference.

We would like to take this opportunity to thank all members of the program committee for their great effort. Working with so many highly dedicated people was truly a great experience.

At the end of the conference, on its last day, the champagne was cold, dry, and free!

FUSION 2005, PHILADELPHIA, PA

JOHN J. SUDANO, GENERAL CHAIR

The FUSION 2005 conference was held at the Wyndham hotel in Philadelphia, PA, July 25–29, 2005. The conference featured three distinguished plenary speakers: Dr. Ted Bially, director of the U.S. Defense Advanced Research Projects Agency/Information Exploitation Office (DARPA/IXO) and a familiar name to fusion engineers; Dr. Allen Waxman, director of multisensor exploitation for BAE Systems Advanced Information Technologies; and Dr. Wilson Felder, director of technology development for the Federal Aviation Administration (FAA). Our sponsors, the IEEE AES Society, the IEEE Philadelphia Section, and ISIF, provided a venue to our membership—engineers, scientists, academics, and end users—and the latest technical advances in the area of information fusion. The participating authors brought forth the best they had to offer their associates and were able to transfer their technologies to a wider base of users, who included 342 attendees from more than 30 nations. Participants were able to upgrade their knowledge and experience in the development and application of fusion system design. In addition, all participants had the opportunity to discuss avenues for international collaboration, as well as to develop long-term relationships among different research centers and academic groups. There were more than 300 peer-reviewed papers, posters sessions, and 17 tutorials representing more than 12 countries.

Subrata Das, Mitch Kokar, Ivan Kadar, Enrique Ruspini, Dan Corkill, and Erik Blasch.

The conference opened on Tuesday morning with Ted's plenary presentation. On Wednesday morning, Wilson was the plenary speaker; aviation technology development is another great application area for information fusion. On Thursday morning, Allen, an image fusion researcher, educated us on the latest technologies as applied to multisensor imagery exploitation, radar range profile fingerprinting and vehicle tracking, and information fusion and mining.

Fulvio Oliveto, Glenn Shafer, John Sudano, Erik Blasch, and James K. Beard.

Dr. Glenn Shafer, the honorary chairman, was a great asset at the conference; he interacted with many participants, especially many younger engineers. The eighth International Conference on Information Fusion would not have been possible without the enthusiastic support and dedication of the organizing committee members, and I profusely thank them.

FUSION 2006, FLORENCE, ITALY

STEFANO CORALUPPI AND PETER WILLETT, GENERAL COCHAIRS

Florence, Italy, offered a wonderful backdrop for an impressive FUSION conference in 2006. The organizational effort benefited from strong support from the nearby North Atlantic Treaty Organization (NATO) Undersea Research Centre (NURC, now the NATO Centre for Maritime Research and Experimentation). The venue itself was a refurbished 16th-century monastery, the Convitto della Calza, that was just the right size for the gathering of nearly 400 participants, a FUSION record at the time. The conference started the day after Italy's impressive World Cup win, so all the Italians were in great spirits!

Craig Carthel, Stefano Marano, Peter Willett, Bob Lynch, Alfonso Farina, Stefano Coraluppi, and Alberto Baldacci.

The conference itself was well planned and executed, with leadership by Dr. Stefano Coraluppi (then of NURC and now at Systems & Technology Research) and Prof. Peter Willett (University of Connecticut). For many, 2006 marked the year in which FUSION really came into its own and combined an excellent technical program with a world-class experience for attendees.

Small but exquisite meeting room.

The conference featured excellent plenaries by Marcel Hernandez, Roy Streit, and Nils Sandell, combining recent cutting-edge research with historical perspectives on advances in distributed fusion. Notwithstanding the high technical caliber of the conference, FUSION 2006 is best remembered for the social program. Roy remembers the welcome reception and banquet dinner as follows: "For me a lasting memory is the welcome in the Palazzo Vecchio. The speech by a city Dignitary [*Assessore Giani*] was translated flawlessly into English by Stefano. That speech in that great and illustrious Hall [*Sala dei Cinquecento*], was a moment I will never forget. Another was the venue of the banquet. Again, absolutely unforgettable with its magnificent view overlooking the city."

Palazzo Vecchio, Florence.

FUSION 2007, QUEBEC CITY, CANADA

PATRICK MAUPIN, TECHNICAL CHAIR, AND ANNE-LAURE JOUSSELME, TECHNICAL AND TUTORIALS CHAIR

Quebec City, Canada, hosted the 10th edition of the International Conference on Information Fusion, July 9–12, 2007, at the hotel Loews Le Concorde on the Plains of Abraham, within the Battlefields Park. The FUSION 2007 attendees enjoyed the Québec City International Summer Festival, a gathering every summer of world-class musical artists. The organizing team was Éloi Bossé (executive chair), Alexandre Jouan (program chair), Pierre Valin, Anne-Laure Jousselme, Patrick Maupin, Henry Leung, and Anne Clément. With 377 participants, the conference saw record Canadian participation (about 30% of the attendees). The 300 papers submitted allowed the selection of about 240 papers to be presented.

Alexandre Jouan, Guy Vezina, Pierre Valin, Eloi Bossé, Anne Clement, Patrick Maupin, and Anne-Laure Jousselme.

The technical program was completed by a selection of tutorials reaching out to the artificial intelligence community with and led by Glenn Shafer, Henri Prade, and Eric Grégoire.

During the gala dinner, the Painchaud Family (three brothers and one sister) entertained the audience, playing classic French-Canadian music mixing stringed instruments (violins, viola, guitar, piano, banjo, etc.). Erik Blasch (Air Force Research Laboratory, Wright-Patterson Air Force Base, OH) was chosen by the band for some exhibition on the stage, and they had him wear his first Canadian shirt. Maybe in anticipation of his future life?

Erik Blasch (center) and the Painchaud Family.

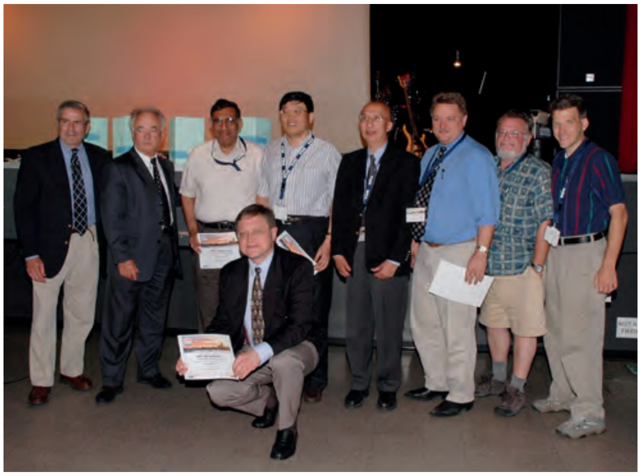
The 10th FUSION conference was an opportunity to innovate in some aspects. In particular, a student sponsorship program supported at the level of 10,000 CAD by the ONR allowed registration fees to be cut in half for qualified students. The best papers were also honored during the welcome cocktail to increase attendance at their subsequent presentations. In addition a forum of two full days was offered for poster presentations, which stimulated participation and discussions. After the conference, Alain Appriou (ONERA, France) confessed that "FUSION 2007 undeniably stands out in the history of our community as a major scientific event."

FUSION 2008, COLOGNE, GERMANY

WOLFGANG KOCH AND PETER WILLETT, GENERAL COCHAIRS

FUSION 2008 was not only the 10th anniversary of ISIF but put Germany on the map of our community. Cologne, the melting pot fusing people, languages, and cultures for more than 2,000 years, was the right choice. Her visible witnesses of a grand culture in the heart of Europe, modern liveliness, and beautiful skyline dominated by the famous cathedral sheltering the Shrine of the Three Wise Men created an atmosphere to discover new frontiers in our innovative branch of knowledge.

The venue by the river Rhine also overlooked a historic site for FUSION, where Christian Hülsmeyer performed his radar experiments in April 1904—one of the first examples of producing situational awareness by sensor data fusion.



Award recipients: Jim Llinas, Yaakov Bar-Shalom, Pramod Varshney, X. Rong Li, Chee-Yee Chong, W. Dale Blair, Pierre Valin, Erik Blasch, and Darko Musicki (in front).

The mayor of Cologne received us in the historic town hall, built on the foundations of the city's Roman governor. One of us, Richard Klemm, the world-known radar scientist and classical pianist, entertained us there with pieces taken from *Carnaval* by Robert Schumann, one of the great sons of the Rhineland, providing us a glimpse of the Rhine Valley Carnaval even in July.

On the flagship of the German Rhine fleet, we had the banquet while cruising and conversing on the waves. Many of us experienced ballroom dancing as a genuine FUSION task. Since this ship also served Benedict XVI when visiting Cologne in 2005, we gave the gift that he received then, a faithful copy of a Roman vase, to the former presidents of ISIF, among whom Yaakov Bar-Shalom seemed like a pope of fusion.

Wolfgang Koch and Peter Willett.

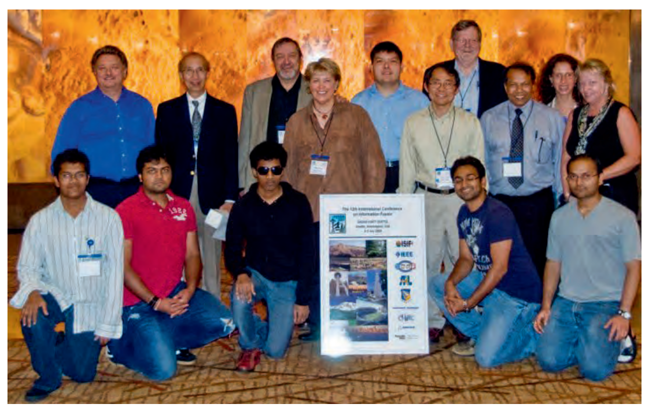
We believe we arranged an extraordinary technical program, with 262 presentations in six tracks. Organizing a top-class conference is a wonderful experience, one of the last real adventures in modern life. It required many hands, heads, and hearts to make it a success.

FUSION 2009, SEATTLE, WA

CHEE-YEE CHONG, GENERAL COCHAIR

FUSION 2009 was held in Seattle, WA, after the Great Recession and during a pandemic. Despite these challenges, the conference managed to set a record in the number of submitted papers, attendance, sponsorship, and surplus due to the tireless effort of the organizing committee and some luck.

Seattle was selected as the conference location partly because it is the headquarters for Boeing, which agreed to sponsor the reception at the Museum of Flight. With Boeing as the lead, the conference also attracted other corporate sponsors, such as Northrop Grumman, BAE Systems, the Cardiff University Brain Research Imaging Centre, the Georgia Tech Research Institute, and Metron. U.S. government research sponsors with international offices—the Air Force Office of Scientific Research, Army Research Laboratory /ARO, and ONR—also provided financial support. It was fortuitous that commitments for support were made before global stock markets crashed in October 2008. Since then, U.S. government agencies have changed their policy and stopped sponsoring the FUSION conferences, including W. Dale Blair, Chee Chong, Robert Lobbia, DiAne Lobbia, S. Jay Yang, Kuo-Chu Chang, Roy Streit, and Mahendra Mallick.



FUSION 2009 organizing committee, including W. Dale Blair, Chee Chong, Robert Lobbia, DiAne Lobbia, S. Jay Yang, Kuo-Chu Chang, Roy Streit, and Mahendra Mallick.

The conference invited three plenary speakers from government, industry, and academia. The government speaker was Dr. Charles Morefield, director of the Information Processing Techniques Office (IPTO) at DARPA. IPTO funded breakthroughs that are technology enablers for information fusion, including the Internet and artificial intelligence. Charles wrote the paper that laid the foundation for track-oriented multiple hypothesis tracking. The industry speaker was Dr. Larry Stone, chief executive of Metron and a member of the U.S. National Academy of Engineering for his contributions to search theory. In 1986, he produced the probability maps used by the Columbus America Discovery Group to locate the *SS Central America*, which sank in 1857, taking millions of dollars of gold coins and bars to the ocean bottom 1.5 miles below. The academia speaker was Dr. Chris Urmson from Carnegie Mellon University and Google, who led the team that won the DARPA Urban Challenge in 2007. He was one of the original leaders of Google's self-driving car project, which later spun off into Waymo in 2016. His plenary talk had little mention of machine learning, which has become the key technology for self-driving vehicles. The technical program also did not have any papers on machine learning.

Tammy Blair (center).

2009 was also a year with a pandemic. In spring 2009, a novel influenza (H1N1) virus emerged. It was detected first in the United States and spread quickly across the United States and the world. Even though it spread quickly, eventually infecting more than 60 million people over 1 year in the United States alone, the mortality rate was low compared to COVID-19. Since there were no travel restrictions, conference attendance was not affected and set a record. However, some people fell sick during the conference. Tammy Blair, the administrative chair, was infected and died a few days after the conference. ISIF established the Tammy Blair Best Student Paper Award in her memory.

Robert Lynch.

Despite the record attendance and financial sponsorship, the record surplus of FUSION 2009 would not have been possible without the extensive use of volunteers for conference management. In particular, Tammy did everything from hotel contract negotiations, to CD cover design, registration support, and too many other things to list. Bob Lynch, the general cochair, was so stressed out that he announced at the conference banquet that he would retire from ISIF. Fortunately, he changed his mind and continued to make important contributions to ISIF operations until he passed away in 2015. The ISIF Robert Lynch Award for Exceptional Service was established in his memory. Most conferences after FUSION 2009 have used conference management companies to support conference administration so that the organizers can focus on the technical program.

FUSION 2010, EDINBURGH, UNITED KINGDOM

SIMON MASKELL, GENERAL CHAIR

FUSION 2010 was hosted in Edinburgh, Scotland, and thanks primarily to the IET's help, was an overtly professionally run conference that attempted to enable ISIF to demonstrate maturity beyond its years: ISIF was 13 years old in 2010. Perhaps unsurprisingly, the conference did suffer from the global recession. It constrained the financial headroom compatible with FUSION 2010 making a surplus, and this limited the physical space allocated for some parallel sessions. However, just like every young teenager coming to terms with financial reality, FUSION 2010 also offered glimpses of an exciting future, perhaps best evidenced by the plenary sessions. Andrew Blake spoke about technology that was subsequently integral to the release of the Kinect console (which was released later in 2010 and went on to sell 8 million units in its first 60 days).

David and Elizabeth Krout.

In the plenary panel session, experts in their respective methodological fields struggled to solve a (deceptively) simple-looking fusion problem involving just three datapoints and a high-impact decision. A particularly memorable moment was when one perceptive panelist asked why we were

Evangeline Pollard, Roy Streit, and Paul Bui Quang.

using math to tackle a problem that is inherently about psychology. Paul Newman spoke about technology for autonomous cars (and has since, among other accolades, gone on to develop the first autonomous vehicle permitted on public roads in the United Kingdom). In that context, FUSION 2010 showed us all that we, as a community, had the capacity to make a difference.

David Salmond, Neil Gordon, Simon Maskell, and Yvo Boers.

FUSION 2011, CHICAGO, IL

DARIN DUNHAM, GENERAL COCHAIR

The FUSION 2011 conference was held in Chicago, IL, and was remarkable in many aspects. The opening reception was on the 99th floor of the Willis Tower and provided the option for attendees to get their picture taken on the glass ledge. The banquet dinner was on Navy Pier, and we had a Blues Brothers–style band that entertained everyone. At one point, there was good conga line dancing. The inaugural 5K race began with Kannappan Palaniappan edging me out for the win by 1 second. About 20 people went to the Chicago White Sox game the evening of the last day of the conference. It was great fun introducing several Europeans to America's pastime.

Peter Willett, Sunshine Smith-Carroll, and Darin Dunham.

Sunshine Smith-Carroll and I volunteered to be chairs, and we didn't have much experience. However, we were well advised by Peter Willett.

The rest of the organizing team was Lance Kaplan, Neil Gordon, Juan Vasquez, Dale Blair, Wayne Blanding, Roy Streit, and David Hall. Coming out of the recession, we thought attendance would surpass 400, as there were 398 people at Edinburgh the previous year. Registration ended up at 364, which was a little disappointing, but we had a great time.

FUSION 2012, SINGAPORE

GEE WAH NG, GENERAL COCHAIR

It was fun organizing FUSION 2012 in Singapore, ideally placed to act as a bridge between west and east. FUSION 2012 attracted a higher volume of participants from Asian countries, besides the regular attendees from Europe and America. The organizing committee worked hard to make the event successful and one of the most memorable, exceeding 500 participants, the highest in the FUSION conference history to that point.

For the first time, we had the program information on mobile apps, in addition to the usual hardcopy. We had the banquet at the Grand Copthorne Hotel, along the Singapore River. Participants loved the 30-minute boat ride. As a Singaporean, I also took such a boat ride for the first time and enjoyed the city view as we cruised along the river.

At my banquet table, I discovered that my general cochair, Prof. Yaakov Bar-Shalom, had taste buds that were unmatched for Asian spicy chili. He took a whole lot of the red-hot chili seeds and said that was still below his expectation on the level of spicy hot. Quietly, I was worried for him, because he had to speak the next morning at the conference. Of course, he proved me wrong, and his voice was as clear as usual the next day, including Yang Rong, Mahandra Mallick, Gee Wah Ng, Yaakov

FUSION 2012 attendees eating durian fruit, including Yang Rong, Mahandra Mallick, Gee Wah Ng, Yaakov Bar-Shalom, Sze-Kim Pang, and Brian Ang.

Gee Wah Ng.

Bar-Shalom, Sze-Kim Pang, and Brian Ang.

I also remember the durian session we had with some conference participants. Durian is the "king of fruits," with a strong odor, and FUSION 2012 fell in durian season.

I also love the T-shirt designed for the FUSION 2012 conference's working committee members and helpers. To this day, I still have the T-shirt with the phrase "Fusion 2012" clearly printed. Once again, I would like to thank every FUSION 2012 participant, the ISIF board members, and the working committee members who made the event successful and a memorable one.

FUSION 2013, ISTANBUL, TURKEY

MURAT EFE AND ROY STREIT, GENERAL COCHAIRS

FUSION 2013 will be remembered as the one that almost got away, as prolonged public protests and clashes between protesters and riot police in the month or so before the conference nearly had it canceled. It did not help that the clashes were in Taksim Square, which looks on a map to be close to the FUSION conference venue and almost across the street from one of the conference hotels. The conference went on after the bold decision by the organizing committee not to cancel and the even bolder decision by the ISIF board to go ahead.

Despite many individual cancellations, 362 people registered for the conference and had an excellent time. A few even boasted that they took part in protests, dodging police-fired gas canisters. In addition to these problems, the travel plans of many U.S. authors and attendees were unexpectedly disrupted through no fault of their own by funding sequestration that was imposed by the U.S. government just days before the conference was to begin. Many hurried accommodations had to be made, but the conference was held and nearly all accepted papers were able to be presented.

Ottoman Marching Band in the main conference hall.

The Askeri Müze (Military Museum), which was a war academy during the Ottoman times, was chosen as the conference venue, and the opening reception was held in the garden of the museum. The first day witnessed a show by the Ottoman Marching Band displayed in the main conference hall. The gala dinner was held on an island of the Bosporus where people had to be taken by boats. A live performance attracted many people to the dance floor. Many conference attendees, along with their companions, enjoyed Istanbul and other attractions all around Turkey before and after the conference.

Memories of Istanbul are precious and extend beyond the conference: a tour of the justly famous Grand Bazaar and a possibly overzealous carpet salesman, a delightful boat cruise on a lovely day up the Bosporus to the edge of the Black Sea that put 2,000 years of history on display, the delicate and exquisite beauty of the Blue Mosque and awe-inspiring antiquity of the Hagia Sophia, and hotel rooftop dinners with good friends overlooking the Hippodrome and the Obelisk of Theodosius.

FUSION 2013 group picture.

This undoubtedly touristy list is incomplete in one special way—it does not describe the joy evident in the citizens of Istanbul as they celebrated Ramadan, which in 2013 encompassed the days of the conference. As the afternoon daylight drew to a close, many establishments set out small tables in public spaces so that, precisely at dusk, the observants would break their daytime fast. Summer days are long, the city is dazzling, and food shared with others is a deep cultural bond. Yes, memories of Istanbul have lasted long after the end of the conference. It is but one example of why ISIF is truly an international society.

FUSION 2014, SALAMANCA, SPAIN

JESUS GARCIA HERRERO, GENERAL COCHAIR

Organizing the 17th edition of the FUSION conference in 2014 was an experience full of challenges and joy, since it was the first time that Spain was the host country for this conference. The proposal was developed by a Spanish-based team (Universidad de Salamanca and Universidad Carlos III de Madrid), inspired by Prof. James Llinas (also with Spanish origins) to combine the standards of our ISIF conference with the local taste of Spanish traditions. The city of Salamanca was selected as an ideal place for this purpose, with a record of hosting international conferences while providing a condensed offering of Spanish history, culture, and services for visitors.

FUSION 2014 attendees and organizing committee, including Fernando de la Prieta, Jose Manuel Molina, Joachim Biermann, Jesus Garcia, James Llinas, Javier Bajo, Kellyn Rein, Geoff Gross, and Eric Little.

We received 386 registered attendees who came from more than 30 countries, with the biggest numbers from United States, Germany, China, Spain, France, the United Kingdom, and Sweden. The conference venue was in the historic part of the city, at the center of the cultural, economic, commercial, and social life.

Tractor-guided tour to see bulls.

The social program included receptions at historic buildings of Salamanca and offered cocktails and Flamenco concerts in known pubs of the city. The place for the banquet dinner had a happy surprise for attendees: Villar de los Alamos was a typical place dedicated to growing purebred Spanish bulls and horses and offered a guided tour on tractors with trailers for visitors to see the bulls in their living place.

FUSION 2015, WASHINGTON, DC

PAULO COSTA, GENERAL COCHAIR

FUSION 2015 was held in the capital of the United States, organized by George Mason University's Center of Excellence in Command, Communications, Computing, Intelligence, and Cyber, with the support of IEEE's AES Society. All conference activities occurred on a dedicated floor at the Grand Hyatt, which is located walking distance from the Washington Mall and provided the focus and convenience to leverage the richness of the technical program. The conference's 389 attendees were presented with 282 articles (out of 357 submissions), across a schedule that included 12 tutorials, 22 special sessions, and various parallel activities. The three plenary speakers, Moshe Kam, Colleen Keller, and Edward Cope, lent their unique spark of excitement to its technical program.

The social program included a reception housed at the Mansion on O Street. Its 100 rooms and more than 70 secret doors offered a unique blend of music museum, executive lodging, restaurant, retreat venue, bed and breakfast, tourist attraction, and treasure hunt locale. Yet the most anticipated event of the social program was the gala dinner, which was held at the National Portrait Gallery.

Giuliana Pallotta, Kathryn Laskey, Anne-Laure Jousselme, Paulo Costa, Thia Kirubarajan, David Crouse, and Pieter de Villiers.

Dinner was served in the Robert and Arlene Kogod Courtyard, an enclosed courtyard with an elegant glass canopy offering a uniquely sophisticated atmosphere. The night's main attraction was a 17-musician jazz band performing a range of numbers that covered various periods of American music.

FUSION 2016, HEIDELBERG, GERMANY

UWE HANEBECK, GENERAL COCHAIR, AND FLORIAN PFAFF, LOCAL ARRANGEMENTS COCHAIR

FUSION 2016 was a large and spectacular event in Heidelberg with various highlights that people still talk about today. Heidelberg is perhaps one of the most symbolic cities in Germany, situated in the heart of Old Europe. Near Germany's oldest and one of its most reputed universities, Heidelberg represents the very idea of European university life that is fusing ideas, attitudes, and mentalities from many countries. Moreover, the romantic ruins of Heidelberg's castle symbolize the successful fusion of former enemies that has become the root of modern Europe.

FUSION 2016 welcome cocktail.

As the venue for FUSION 2016, we selected the Kongresshaus Stadthalle Heidelberg (Heidelberg Convention Center) as it is centrally located and can be reached easily.

Fredrik Gustafsson in the Kongresshaus main room.

With its sumptuous, late 19th-century architecture and flashes of art nouveau brilliance, the Kongresshaus formed a stunning backdrop for more than 20 tutorials and 300 oral presentations that were organized in 44 regular and 22 special sessions. Thirteen function rooms provided 2,500 m^2 of floor space for our 451 participants and 28 registered accompanying people. Various industry sponsors supported the event financially and with exhibitions during the event. Memorable social events include the 5K run along the river, the welcome reception in the spacious foyer at the conference venue, and the gala dinner at the Technic Museum Speyer.

Uwe Hanebeck.

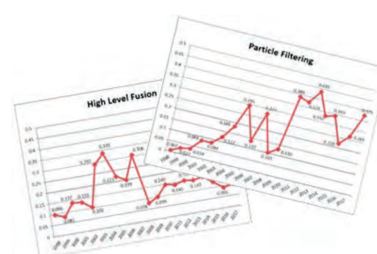
FUSION 2017, XI'AN, CHINA

X. RONG LI, GENERAL COCHAIR

What was most unique, memorable, and interesting at FUSION 2017 was its 20th-year special program to celebrate the anniversary. Well, this was debatable: While our preparation of the special program was in full swing, a well-known fusion expert (Shozo Mori) pointed out that 2017 marked the 19th (not the 20th) anniversary of the FUSION conference, because the first anniversary was the second FUSION conference (FUSION 1999). This was devastating for us yet rigorous in the academic sense, albeit a distinction often overlooked in practice. By the same token, the new millennium started in 2001, not 2000 as everyone thinks. As an engineering professor, I wanted both practicality and academic rigor, so the "20th Anniversary Program" was renamed the "20th-Year Special Program."


Song of Everlasting Sorrow show.

The work for this special program was most challenging and time consuming, so much so it was probably more than all other work combined for organizing FUSION 2017. The most challenging item was the "Area Trend in Information Fusion," including in particular: identifying representative topical areas, finding objective ways to reveal the trend, collecting relevant data, and making valuable observations about the trend. Knowing the value of such a trend analysis for the fusion community, the organizing team spent countless hours on this task and sought outside help. Following the principles that the results should (a) be as objective as possible, (b) show the 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 keywords (phrases) to represent each area and show their relative occurrences to indicate trends.

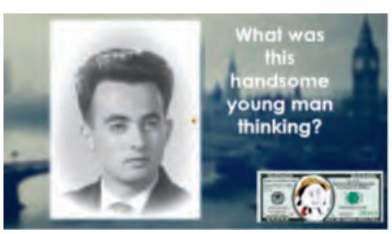


FUSION topic trends [2].

The special program also had many other components, including providing the following of all FUSION conferences up to 2017: important facts (e.g., organizing teams, plenary talks, best [student] paper awards, tutorials, and special sessions); useful statistics (e.g., countries, organizations, and people who contributed most, as well as topics that were most popular, as reflected in the form of word clouds); recognition of those who contributed most in conference attendance, technical contributions, or conference service; and obituaries of fusion experts. All these are still available on the FUSION 2017 website under ISIF.org, and a report of the program appeared in *ISIF Perspectives on Information Fusion* [2].

20 years of FUSION word cloud.

Another unique, important, and memorable component of FUSION 2017 was the "Workshop on Fusion, Tracking, and Estimation—A Tribute to Yaakov Bar-Shalom," in recognition of his meritorious contributions at his 75th birthday. The workshop consisted of an afternoon session and an evening session. In the afternoon session, Yaakov made a presentation, and a representative group of his Ph.D. graduates and former research associates—Kuo-Chu Chang, Jean Dezert, X. Rong Li, and Thia Kirubarajan—each made an academic presentation as a tribute to the professor. As the organizer, I also made welcome remarks and presented important facts of Yaakov's academic contributions as a scholar and as a teacher, such as books, publications, and students, including in particular his academic genealogy and two word clouds, one for the keywords in his publications and the other for his research collaborators. The evening session was full of fun and enjoyed by everyone there. An interview of Yaakov with interesting questions was conducted. A recorded dancing performance of several of his Ph.D. graduates and research associates in a cartoon style was presented. Based on a real record with many representative photos of Yaakov, starting from his infant time, a movie of an imaginary story was shown about a "lost kid YBS" coming back that inspires young people to follow in his footsteps to pursue their romance.



Movie in tribute to Prof. Yaakov Bar-Shalom.

FUSION 2018, CAMBRIDGE, UNITED KINGDOM

LYUDMILA MIHAYLOVA, GENERAL COCHAIR

The 21st International Conference on Information Fusion was in the memorable city of Cambridge, United Kingdom. The general chairs for the event were Prof. Simon Godsill, Prof. Simon Maskell, and myself.

Karl Granström, Emre Özkan, Simon Godsill, Lyudmila Mihaylova, and Erik Blasch.

It was attended by more than 500 participants from academia, industry, and other organizations. The conference was remarkable in many aspects—from the venue to inspiring discussions, sessions, and networking opportunities, well attended by both academics and industrial representatives. FUSION 2018 took place in the Department of Engineering at the University of Cambridge, which is centrally situated on Trumpington Street.

Welcome reception at St John's College.

The city of Cambridge has attractive architecture, both ancient and modern. Cambridge is at the heart of the high-technology center dubbed Silicon Fen, with its economic strengths from industries such as software and bioscience and many start-up com-

Simon Godsill introducing the keynote of Neil Gordon.

panies that have spun out of the university. The dinner was held in the Duxford Museum. Participants were able to enjoy reception drinks under the wings of some of the world's most iconic aircraft, including a Concorde, before being seated for dinner.

The celebration of the 25th anniversary of particle filter was one of the remarkable events, with a talk by Neil Gordon, David Salmond, and Adrian Smith. It sparked interesting discussions and inspired ideas for the next generations of methods beyond particle filters. FUSION 2018 showed that the vibrant fusion community is expanding across multiple disciplines.

FUSION 2019, OTTAWA, CANADA

ELISA SHAHBAZIAN, GENERAL COCHAIR, AND MIHAI FLOREA, LOCAL ORGANISATION CHAIR

In July 2019, Canada hosted the FUSION conference for the third time, after Montreal in 2001 and Quebec City in 2007. Ottawa, Canada's capital, is a hub of knowledge-based industries, research institutes, and higher education, with more engineers than any other Canadian city, many active in information fusion and related fields. It was thus a natural choice for welcoming the international community of information fusion on July 1, Canada Day. The Shaw Centre offered a perfect venue in downtown Ottawa, near the Rideau Canal. James Llinas and myself were general cochairs, supported by Mihai Florea as local organizer. The attendance was quite high (above 400 participants), as was the number of submissions received (372). We proposed a rich program focused on advancing multidisciplinary and innovative methods for solving the most challenging problems in the field, inclusive of methods that could be called disruptive to traditional concepts in data and information fusion. We favored student participation with initiatives such as the student pass, which allowed students to attend three tutorials at a very low cost. During coffee breaks, FUSION 2019 attendees could visit exhibits and demonstrations in the hallways and discuss posters with their authors, as well as visit the booth for the next year's conference (2020). The invited conference keynote and panel speakers discussed novel data fusion methods, as well as challenges for fusion in novel application domains. The keynote of Tracey Lauriault from Carleton University, Ottawa, Ontario, on data fusion in the open smart city context led to the first interview of the *Perspective* magazine, published in issue 3. The 5K run took place early in the morning on the first day of the conference on the shores of the Rideau Canal, which connects Ottawa to Lake Ontario and the Saint Lawrence River at Kingston, Ontario.

Elisa Shahbazian.

Mihai Florea.

FUSION 2020 booth.

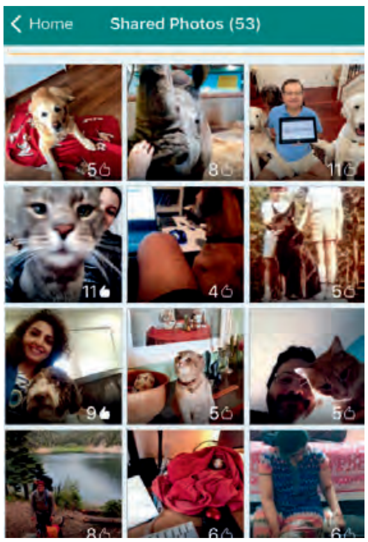
Ottawa's Canadian Museum of History.

The gala dinner was held at the Canadian Museum of History. The museum's spectacular Grand Hall and River Salon houses the world's largest indoor collection of totem poles. Guests had the chance to visit the museum prior to the gala dinner. The museum was open for the participants to browse before dinner.

FUSION 2020, VIRTUAL

PIETER DE VILLIERS, GENERAL COCHAIR

ISIF hosted its 23rd International Conference on Information Fusion online, July 6–9, 2020. On April 2, 2020, the ISIF Board of Directors and the South African Local Organising Committee, in consideration of the effects of the COVID-19 pandemic, decided to proceed with the FUSION 2020 conference hosted as a virtual online event. Dr. Paulo Costa, the 2020 ISIF president, announced, "Witnessing the strong participation of our community, ISIF and the FUSION 2020 organization jointly opted for conveying the conference in a virtual format only, while keeping all the technical program intact." The program did not deviate substantially from the original conference agenda, with the only component omitted being the social events. The conference was attended by 278 people and featured 16 tutorials and 169 papers that were viewed by attendees from 24 countries.



"Pose with your pets" competition.

The hosting of FUSION 2020 was an exciting prospect since our successful bid to the ISIF Board of Directors in Xi'an, China, at the 2017 FUSION conference. I clearly remember the anticipation and relief as we heard that our bid was successful. The subsequent years were filled with an increasing level of work and commitment to plan and prepare for this conference, and it was our greatest wish to offer the regular and new attendees a conference experience that they would not forget. Alas, COVID struck and our hopes were dashed. We scurried to get the infrastructure in place for a virtual conference and managed to get the support of the board to postpone the onsite event to 2021. Little did we know that the pandemic would still persist throughout 2021. Nonetheless, we managed to host the online event, and there was quite significant social media interaction among attendees via the Whova app we used. Thanks to our loyal and capable army of reviewers, we managed to keep the technical quality of accepted papers at the high standard that was a hallmark of previous FUSION conferences.

I have some charming memories of social interactions that resulted from the "pose with your pets" competition initiated by Alta de Waal on the conference app. It was also satisfying to see the presentations and attend discussions on the live question-and-answer (Q&A) sessions, in which the paper presentations were discussed. These ran mostly smoothly because of the excellent efforts of the session chairs. I was pleased that the efforts of the organizing team and relevant chairs paid off. We managed to keep FUSION alive in the midst of a global pandemic.

ALTA DE WAAL, GENERAL COCHAIR

Hosting an online conference when no one could fathom such a concept only 3 months prior is a stressful experience. Multiple time zones and parallel tracks added to the complexity. It was a deep disappointment not to host the conference after we had so many plans to make it special and memorable in South Africa. However, as Napoleon said, "A genius is the man who can do the average thing when everyone else around him is losing his mind." We are no geniuses but strived to provide a platform for the fusion community to engage their research—as best as we could—when it would not have been frowned upon to skip the conference. We are proud of that we kept up the FUSION conference momentum, which is the heartbeat of the community, during the pandemic.

FUSION 2021, SUN CITY, SOUTH AFRICA

ALTA DE WAAL, GENERAL COCHAIR

The ISIF hosted its 24th International Conference on Information Fusion at the Sun City Convention Centre in Rustenburg, South Africa, November 1–4, 2021. The conference was attended by 214 people, of whom a quarter attended onsite. We were still able to attract 211 paper submissions, of which 146 were accepted. This equates to an acceptance rate of 69%. FUSION 2021 was hosted at a superb conference venue, the Sun City Convention Centre. Sun City is situated a mere 200 km from Johannesburg and borders Pilanesberg National Park, allowing participants to see the Big Five animals of Africa.

Alta de Waal.

The physical hosting of FUSION 2021 was constantly on a knife edge, and looking back, the conference dates were planned perfectly in a period when the COVID wave in South Africa was at its lowest. Two weeks later, the Omicron variant hit South Africa, and it goes without saying that the onsite dream would have been destroyed. Although the physical presence was small, it encouraged more interaction, especially between students and more experienced researchers. It was a special and intimate conference, although the presence of online attendees could be felt through the hybrid format.

PIETER DE VILLIERS, GENERAL COCHAIR

Never in the history of the FUSION conference was it ever expected of an organizing committee to arrange two successive FUSION conferences. That opportunity fell into the lap of the South Africa FUSION organizing team. The onsite 2020 conference was first postponed to July 2021 and then November 2021 because of the COVID pandemic that simply did not want to relent. We were offered a fortunately timed window in November, when infection rates dropped to almost zero in South Africa, just before the Omicron variant struck. We managed to assemble a group of local and international attendees at Sun City, Rustenburg, South Africa, and the group of about 70 was large enough to feel like a small crowd. The rest of the 200+ participants attended virtually.

FUSION 2021 attendees, including Keith LeGrand, Samantha LeGrand, Lisa Leishman, Robert Leishman, and Molahlegi Molope.

Those who managed to travel to the venue were treated to exquisite meals; hot, sunny weather; luxury accommodation; and breathtaking game viewing in the neighboring Pilanesberg National Park. The onsite component also allowed those who attended virtually to have the feeling that there were people in the room and stimulated live questions and discussions. This was an improvement over what was possible the previous year, where the prerecorded presentations and the Q&A sessions were somewhat disjointed.

Leopard sighting on the golf course.

On the way to the boma braai (bonfire and barbecue), some attendees were treated to a rare leopard sighting on the golf course. The knowledge of this event made some hesitant to attend the FUSION fun run, which took place on the same golf course the next day. However, others improved on their times. The gala dinner was a treat. The food and wine were exquisite, and there was live entertainment by impressive gumboot dancers. It was a night to remember. Where FUSION 2020 survived on life support, the 2021 conference received a jolt, and the heart of the conference has started beating again. We look forward to the conferences in Linkoping, Sweden, and Charleston, SC, where FUSION will be on the mend and going from strength to strength.

FUSION 2022, LINKOPING, SWEDEN

FREDRIK GUSTAFSSON, GUSTAF HENDEBY, AND TERENCE VAN ZYL, GENERAL COCHAIRS

It feels like a long time has passed since we presented our winning bid in Cambridge, United Kingdom, in 2018. Indeed, the COVID-19 pandemic has interrupted our planning in many ways. First, the conference was postponed 1 year to give South Africa a second chance to organize an onsite conference. Second, it has been difficult to plan with so many uncertainties involved, since many issues around the local arrangement depend on how the pandemic will develop. Luckily, we have close collaboration with the local conference organizer, conference venue, and hotels, whose staff have been understanding. There have been no extra costs for the cancellation in 2021, and no binding contracts have had to be signed.

FUSION 2022 conference venue.

At the time we wrote these lines (March 2022), we had around 230 paper submissions for the 2022 conference. We had expected about double the amount. It seems that the aftermath of the pandemic is still affecting many potential authors. There are travel restrictions in place, concerns about new COVID waves, and possibly a new era that has started with less traveling, particularly overseas. In any case, the organization committee and the ISIF board have a strong preference to get back to the old normal again, with a fully onsite conference. To be prepared for provable circumstances, such as travel restrictions and visa issues that would prevent onsite participation, we will allow for prerecorded presentations. Unfortunately, there will be no provisions for virtual attendance. We hope that this will give the attendees the usual conference experience, with negligible risk for technical struggles and avoiding the somewhat impersonal feeling in mixed onsite–online sessions. We have marketed FUSION 2022 as the most normal FUSION conference ever. Let's hope this comes true.

PHOTO CREDITS

(In alphabetic order) Chee-Yee Chong, Stefano Corraluppi, Paulo Costa, Jean Dezert, Darin Dunham, Murat Efe, Rob Evans, Mihai Florea, Jesus Garcia, Fredrik Gustafsson, Uwe Hanebeck, Alexandre Jouan, David Krout, X. Rong Li, Gee Wah Ng, Florian Pfaff, John Sudano, Pieter de Villiers, Alta de Waal, and Peter Willett.

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2. Li, R. X., and Han, D. The 20th-year special program of FUSION 2017. *Perspectives on Information Fusion,* Vol. 2, 1 (June 2019), 5–13.

1	FUSION 1998	Las Vegas, Nevada, USA	Dongping Daniel Zhu, Rabinder N. Madan
2	FUSION 1999	Sunnyvale, California, USA	Dongping Daniel Zhu, Mark Bedworth, Xiao-Rong Li
3	FUSION 2000	Paris, France	Alain Appriou, Jean-Pierre Le Cadre, Jean Dezert
4	FUSION 2001	Montréal, Quebec, Canada	Jacques Hurtebise, Éloi Bossé, Elisa Shahbazian
5	FUSION 2002	Annapolis, Maryland, USA	Xiao-Rong Li
6	FUSION 2003	Cairns, Queensland, Australia	Rob Evans
7	FUSION 2004	Stockholm, Sweden	Per Svensson
8	FUSION 2005	Philadelphia, Pennsylvania, USA	John Sudano, James K. Beard
9	FUSION 2006	Florence, Italy	Stefano Coraluppi, Peter Willett
10	FUSION 2007	Quebec City, Quebec, Canada	Éloi Bossé, Alexandre Jouan
11	FUSION 2008	Cologne, Germany	Wolfgang Koch, Peter Willett, Jürgen Grosche
12	FUSION 2009	Seattle, Washington, USA	Chee-Yee Chong, Robert Lynch
13	FUSION 2010	Edinburgh, Scotland, UK	Simon Maskell
14	FUSION 2011	Chicago, Illinois, USA	Darin Dunham, Amy Sunshine Smith-Carroll
15	FUSION 2012	Singapore	Gee Wah Ng, Yaakov Bar-Shalom
16	FUSION 2013	Istanbul, Turkey	Murat Efe, Roy Streit
17	FUSION 2014	Salamanca, Spain	Juan M. Corchado, Jesus Garcia, Jose Manuel Molina
18	FUSION 2015	Washington, DC, USA	Paulo Costa, Kathryn Laskey
19	FUSION 2016	Heidelberg, Germany	Uwe Hanebeck, Wolfgang Koch
20	FUSION 2017	Xi'an, China	Xiao-Rong Li, Roy Streit
21	FUSION 2018	Cambridge, England, UK	Simon Godsill, Lyudmila Mihaylova, Simon Maskell
22	FUSION 2019	Ottawa, Ontario, Canada	Elisa Shahbazian, Jim Llinas
23	FUSION 2020	VIRTUAL	Pieter de Villiers, Alta de Waal, Fredrik Gustafsson
24	FUSION 2021	Sun City, South Africa	Pieter de Villiers, Alta de Waal, Fredrik Gustafsson
25	FUSION 2022	Linköping, Sweden	Fredrik Gustafsson, Gustaf Hendeby, Terence van Zyl

25 FUSION conferences, locations and chairs.

26th International Conference on Information Fusion
June 27-30, 2023

Charleston, South Carolina, will be home to the 26th International Society of Information Fusion Conference from June 27-30, 2023. For nine straight years, *Travel + Leisure* readers have rated Charleston the #1 city in the United States. The city was founded in 1670 and has preserved a rich history from the American Revolutionary and Civil Wars. Characterized by walkable cobblestone streets, southern plantations and horse-drawn carriages, historic churches, world renowned restaurants and pubs, and all the sights of a waterfront port city and prior naval base, Charleston is a destination to satisfy just about any craving! The conference will be held at the historic Charleston Place Hotel, which is in the center of the King Street historic district adjacent to the City Market, Old Exchange, Provost Dungeon, and Gibbs Museum of Art. The venue is only a short distance from the Battery Promenade and Waterfront Parks overlooking the Charleston Harbor and Fort Sumter, where the first shots of the Civil War were fired. Finally, there are numerous renowned golf courses, barrier island beaches, and national parks only a short drive away. Come and let us share our southern hospitality!

The International Conference on Information Fusion has long been recognized as a premier forum for researchers and practitioners to exchange ideas in the field of information fusion and its impacts on our society. Authors (researchers, students, and practitioners) are invited to submit original papers (between 5-8 pages) describing advances in the theory and applications of information fusion. Topics related to information, sensor, or data fusion in an array of areas including theory and representation, algorithms, applications, methods/tools, modeling/evaluation, and artificial intelligence are welcome. FUSION 2023 proceedings will be published by the IEEE in IEEEXplore and is Scopus indexed.

IMPORTANT DATES:

- February 1, 2023 — Proposals for special sessions and demonstrations (Notification of Acceptance Feb. 10)
- March 1, 2023 — Full paper submission (Notification of Acceptance May 1)
- April 1, 2023 — Proposals for tutorials (Notification of acceptance April 15)
- June 1, 2023 — Final paper submission

For more information on the conference and call for papers visit: https://fusion2023.org

ISIF IEEE

See you soon!

AUTOMATION IN UAV REMOTE DELIVERIES

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Deliveries of post and medical supplies using Uncrewed Aerial Vehicles (UAVs) have seen a notable increase in development over the last few years. This development has, in part, been boosted by the COVID-19 crisis, but also by easy access to low-cost electronics equipment that would normally only be accessible to defense industry (e.g., accurate Global Navigation Satellite System and SATCOM solutions).

Windracers' ULTRA's first flight at Llanbedr Airfield.

While most competing organisations have focused on the last mile of small package deliveries, researchers at the University of Southampton, in partnership with Windracers Ltd., have developed an aircraft that can carry food and medical supplies for a country the size of South Sudan. Even though the range and payload capability are unique (100 kg over 1,000 km), the main benefit over smaller platforms is the aircraft's ability to continue operations even in adverse weather conditions—something that has hindered the widespread use of smaller platforms.

Mail delivery by UAV for the Isles of Scilly.

Throughout 2020 and 2021, development team members were involved in several firsts for UK uncrewed aviation. Successful beyond visual line of sight flights were conducted from the mainland UK to several smaller islands, including Isle of Wight, Isles of Scilly, Orkney Island, Fair Isle, and North Ronaldsay (projects that were in part supported by Royal Mail). Most of these projects were sponsored by Innovate UK's Future Flight Challenge program.

With demonstration flights planned in 2022, the team is aiming to demonstrate how UAVs can become a normal part of the supply chain, particularly for the UK's island communities whose logistics are often expensive and at the mercy of the weather.

Windracers' ULTRA beyond visual line of sight flight to the Scottish island Eday.

Windracers' ULTRA waiting to be loaded with cargo at Isles of Scilly Airport.

NATO – SCIENCE AND TECHNOLOGY ORGANIZATION – LECTURE SERIES

The Lecture Series is organized by the SET Panel of NATO STO (SET-290/RLS)

Artificial Intelligence for Military Multiple Sensor Fusion Engines

Rome (Italy)
September 26- 27, 2022

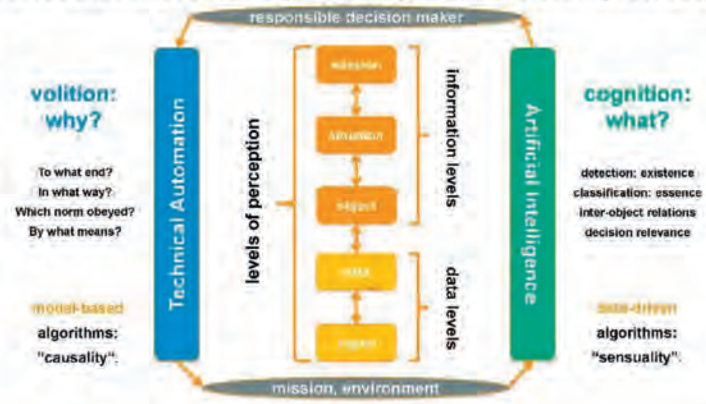
Wachtberg (Germany)
September 29-30, 2022

Budapest (Hungary)
October 3-4, 2022

Cost-free, open to citizens from NATO member states, Australia, Finland, Sweden, Switzerland.

THEME

Digitalization enables military decision-makers to consciously perceive and responsibly act even in the highly complex and accelerated technosphere of modern conflicts. If applied to Military Multiple Sensor Fusion Engines, the methods of Artificial Intelligence (AI), a world of data-driven and model-based algorithms, combined with comprehensive automation become game changers by transforming vast data streams from many sources into situation pictures by an optimized use of available sensing, communications, and platform resources. For this reason, there is an ever increasing need to provide insight into the strengths and weaknesses, opportunities and threats of AI-based perception and decision making in the military domain. The targeted audience of the lecture series are systems engineers, project managers, sponsors, military end-users that have to define requirements. Its main objective is to disseminate the existing knowledge on sophisticated AI algorithms, the very driving forces of advanced Multiple Sensor Fusion Engines. An equally important objective is to encourage further R&D on AI in Defense according to NATO's mission.



TOPICS

In a tutorial fashion, the lecturers will present core methodologies and proven AI algorithms that solve various aspects in military situational awareness and decision making under uncertainty. Besides data from multiple heterogeneous sensors, the team will discuss the exploitation of context information for designing 'cognitive' Fusion Engines that inherently respond to changing scenario and mission requirements. Multifunctionality will be a predominant factor to achieve specialized goals. Emphasis will also be placed on data integrity and security aspects. This comprises selected and unclassified Electronic Warfare issues. Advanced AI methods and examples taken from: probabilistic reasoning, statistical decision making, big/tall/sparse data fusion for tracking, classification, anomaly detection, Bayesian and machine learning, explainable AI, knowledge-representation, multiple hypothesis and logical analysis, sensor and resources management, examples from military applications.

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- Latest Enrolment: 2 weeks prior LS date, enrol online at https://events.sto.nato.int. If you are unable to enrol via the internet, please contact: lectureseries@cso.nato.int

Book Review

Systems Engineering and Artificial Intelligence

William F. Lawless, Ranjeev Mittu, Donald A. Sofge, Thomas Shortell, and Thomas A. McDermott

Springer 2021, ISBN: 978-3-030-77282-6

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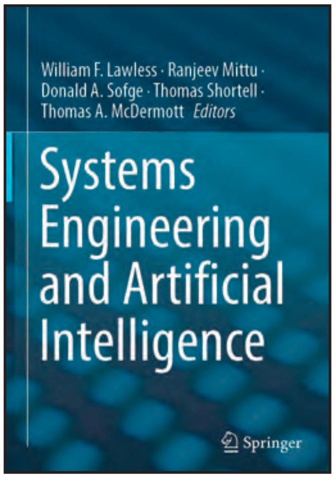
INTRODUCTION

This book presents a wide collection of analysis and examples around the design of Artificial Intelligence (AI) and Machine Learning (ML) systems from the point of view of Systems Engineering (SE). Some relevant aspects covered in the book are, among others, verification and validation of complex systems based on AI/ML, autonomy, emergent behavior, and human-machine teaming. It contains 25 chapters, providing a rich variety of views, disciplines, and examples in different domains, with an extensive analysis of literature on these topics.



Artificial Intelligence is one of the most disruptive technologies in recent years, boosted in part by the decision of big technological companies to integrate it into their business models. It has already shown a significant economic impact worldwide, with even more economic and social impacts to come [1], [2]. According to the Gartner CIO 2019 survey, the volume of organizations that have implemented AI has grown by 270% in the period 2015–2019 [3].

The basic idea behind traditional ML methods is training computer algorithms with data collected in a domain to learn a certain behavior (e.g., self-driving cars) so that an outcome can be produced by the computer algorithm when it is presented with a novel situation [4]. A methodological approach is needed to put these systems in complex, dynamic situations, after following appropriate testing and evaluation methodology. In the Gartner forecast report for 2021 [5], the importance of incorporating AI engineering into business strategy is cited to make investments in AI profitable by improving performance, scalability, interpretability, and reliability of AI-based models.

The book motivates thinking about the open challenges and important issues to develop intelligent, autonomous systems. Interaction and collaboration in human-machine teams, including context sharing to improve mutual understanding, is an interesting view, contrasting with the fear of autonomous, opaque machine learning algorithms that eventually may outperform human skills. This need to improve the understanding of autonomy is associated with the timely decisions that may need to be made faster than humans can process [6], mentioning as examples military scenarios and the push for quicker command, control, and communication upgrades, and also the common use of AI in transport systems like self-driving cars, trucks, ships, or subways.

The application of AI/ML raises several concerns and questions for SE. The usual procedures and metrics of formal verification, certification, and risk assessment must be defined for autonomous systems at the design, operation, and maintenance stages [7], [8]. Specifying performance metrics for emergent behavior opens interesting questions, such as how systems engineers shall assure that the "pieces work together to achieve the objectives of the whole" [9], how to define metrics to assess the risks associated with collaboration, and also how they can be calculated [10].

A central aspect is defining interdependence from a system's perspective, analyzing the interactions and interfaces among subsystems, and dealing with the whole system across its life cycle. Interdependence is a very relevant term in SE, AI, and the science of human–machine teamwork. As hypothesized by the editors, "the best teams maximize interdependence to communicate information via constructive and destructive interference", the optimum team size occurs when they are freely able to choose to minimize redundant team members [11], [12].

CHAPTERS REVIEW

Given the big size of the book, only a few chapters have been selected for this review, to summarize their contents and give a more detailed idea of the book's scope. This selection is a "sample" in the sense that it would serve for this purpose of presenting the main ideas and offer very interesting illustrative examples focused on SE, autonomy, or human-machine interaction. Readers are encouraged to go through all of the chapters to get a rich collection of thoughts, practices, and examples from different perspectives.

CHAPTER 2. "RECOGNIZING ARTIFICIAL INTELLIGENCE: THE KEY TO UNLOCKING HUMAN AI TEAMS" BY PATRICK CUMMINGS, NATHAN SCHURR, ANDREW NABER, CHARLIE, AND DANIEL SERFATY

This chapter was prepared by a team that included an artificial embodiment, "Charlie", in collaboration with other three human co-authors. It presents direct insights generated after co-working with Charlie: how she came into existence, how she operates in public, and how she can be influenced by both human and artificial coworkers and by their contributions.

The chapter starts by distinguishing the two different types of human-IA collaboration and embodiment internal state: supportive collaboration, in which a human and an AI agent together serve as a single member for the team; and participatory collaboration, in which the AI agent is an individual team member, a situation where the AI agent communicates and coordinates with fellow human teammates, a fundamental aspect linked to the progress of the AI field.

The authors present Charlie's embodiment interface and the iterations to refine her communication and representation states driven by feedback. As indicated by the authors, in the case of chatbots, response delays may be acceptable, especially in responses to other panelists. However, to participate with physical and audible queues—gestures used by humans—Charlie had to effectively coordinate the use of the display and audio to achieve a similar presence and clearly represent its internal states.

Many people are aware of sophisticated conversational agents like Watson or AI Debater, thanks to public demonstrations. Moreover, most people interact frequently with conversational agents as customer service chatbots and virtual personal assistants. The developments presented in this chapter around Charlie touch several AI domains, from AI interaction with humans (covering user interface or explainability from AI to human) to integrations into a workplace or team. As reported, Charlie showed advanced capabilities for interaction, such as participating in a panel discussion, speaking during podcast interviews, contributing to a rap battle, catalyzing a brainstorming workshop, and even collaboratively writing the chapter.

> ***"Interaction and collaboration in human-machine teams, including context sharing to improve mutual understanding, is an interesting view contrasting with the fear of autonomous, opaque machine learning algorithms."***

CHAPTER 3. "ARTIFICIAL INTELLIGENCE AND FUTURE OF SYSTEMS ENGINEERING" BY THOMAS A. MCDERMOTT, MARK R. BLACKBURN, AND PETER A. BELING

This chapter was written by experienced systems engineers, who review the transformations expected in their area due to new digital tools for modeling "digital twins", resulting in the integration of data and modeling. They refer to an envisioned long-term outcome, "Human–Machine Co-Learning", referring to a future scenario where both humans and machines will adapt their behavior over time by learning from each other or alongside each other. This new context implies a significant transformation of SE methods, processes, tools, and practices over time.

To achieve this end state, the authors consider several "waves" or eras to be visited by AI and SE disciplines. The first of them includes "Explainable AI", covering technologies and approaches that make the decisions produced by AI systems more transparent to human developers and users. It also includes more transparency and understanding of the methods and tools used to develop AI applications, the underlying data, and the human–machine interfaces that lead to effective decision-making in the type of complex systems SE deals with routinely.

Secondly, the "robust and predictable" wave is to produce systems that learn and may be non-deterministic, but also appropriately robust, predictable, and trustworthy systems, using common aspects to the application of SE practices today. This wave particularly includes both human and machine behaviors in joint decision environments, highly reliant on good human-system design, and presentation of decision information. It also includes the adaptation of test and evaluation processes to co-learning environments.

Finally, the third wave involves systems that adapt and learn dynamically from their environments. In this wave, machine-to-machine and human-to-machine (in both directions) trust will be critical. Trust implies a dependence between the human and machine, and it normally requires the human to understand and validate the performance of the system against a set of criteria in a known context.

The authors identify the key research areas to achieve these waves, such as data collection and curation, ontological modeling, information presentation, digital twin automation, explainability, etc., identifying their use and association with the goals indicated. For instance, the human analysis and decisions will require better understanding and trust in the machine-generated analysis and decisions, or cognitive bias induced in sampled data or algorithms must be reduced to avoid unexpected results of the system making it inappropriate for use.

CHAPTER 6. "SYSTEMS ENGINEERING FOR ARTIFICIAL INTELLIGENCE-BASED SYSTEMS" BY JAMES LLINAS, HESHAM FOUAD, AND RANJEEV MITTU

In this chapter, the authors give a historical review of SE for AI-based systems over time. The chapter starts with a brief history of AI and its main categories (narrow, weak, and strong AI) and an interesting taxonomy of all areas of research, organized in AI techniques and problems addressed [13]. Regarding SE, the current engineering challenges of systems-of-systems and enterprise systems are reviewed, how the concept of life cycle has been evolving thanks to Agile development first, and then to "DevOps" methodologies, to increase the link between software development and IT operations.

Software engineering changes are also included in the review, referring to the well-known "Waterfall" development methodology originally proposed for "large computer programs", and its current progression to face challenging aspects of developing AI/ML systems, such as their strong dependency on the data used. The AI/ML life-cycle model requires dealing with data, selecting a target model, and training and testing it under different configurations and performance metrics. The process must define the logic involved in selecting the data to learn in relation to targeted purposes of the application, requiring non-trivial domain knowledge, and considering non-linear interdependencies [14]. In addition, another key step in SE is formed by test and evaluation processes. Model-Based Test defines models for describing test environments and strategies, generating test cases, etc. to trace the correspondence with requirements and models used in design. In the case of ML, the problem is about model testing for classification to a great degree, and AI is about possibly complex layers of inferencing. Some paths are mentioned for the selection of the test and evaluation processes and metrics for both types of systems.

Finally, the emergent behavior is addressed, as a key property of complex systems, linked to the open issue of explainability in AI and ML. The authors close the chapter by discussing the challenge of AI explanations and explainability, with the aim to solve the Black Box problem through post-hoc analysis, or in an alternative approach using interpretable systems. Impenetrableness of most AI/ML systems comes from difficulties in knowing how inputs are transformed into outputs and which environmental features and regularities are being used.

CHAPTER 8. "RE-ORIENTING TOWARD THE SCIENCE OF THE ARTIFICIAL: ENGINEERING AI SYSTEMS" BY STEPHEN RUSSELL, BRIAN JALAIAN, AND IRA S. MOSKOWITZ

This chapter is focused on engineering design aspects of AI-enabled systems, explained by authors in the military domain, where these systems are becoming pervasive and must face specific challenges. They discuss hierarchical component composition in a system-of-systems context and focus on the stability problems for this type of complex systems, in relation to their level of connectedness. As indicated, system instability appears when emergent behaviors that are not anticipated take place. Moreover, the logic incorporates ML models, which depend on the data used to build them and the data with which it interacts. Therefore, the importance of bounding data for stable learning is highlighted.

Another aspect that is highlighted are the design/engineering problems of interoperability since AI systems usually operate as an element of a multi-component system. The authors refer to the discipline of systems theory, which emphasizes understanding the behavior of the system (e.g., a realized assembly) as a function of the behavior and interaction of its constituent elements (components). Challenges in cascading deployment are particularly relevant to AI systems because the boundaries that typically define system locality can be greatly expanded and obfuscated, leading to emergent system behaviors.

Finally, the presence of uncertainty in any system process opens an opportunity for emergent behavior that expands the boundary of the system's functions. Modern AI is particularly prone to introducing uncertainty into its outputs because of its reliance on ML algorithms. The authors illustrate system engineering problems described in the chapter, using examples of natural language processing (NLP). NLP tasks typically require multiple ML methods to be applied sequentially to achieve the objective of content understanding and are impacted by uncertainty in each step. The NLP system was designed to process the content of weekly activity reports prepared by information science researchers at the Army Research Laboratory, aimed to identify documents about similar topics and present a graphic summary of the relationships found. The example was used to illustrate the described challenges of AI system engineering and how the manipulation of a few hyperparameters made the experimental AI system significantly change its output.

> ***"The application of AI/ML raises several concerns and questions for SE. The usual procedures and metrics of formal verification, certification and risk assessments must be defined for autonomous systems at the design, operational and maintenance stages."***

CHAPTER 10. "DIGITAL TWIN INDUSTRIAL IMMUNE SYSTEM: AI-DRIVEN CYBERSECURITY FOR CRITICAL INFRASTRUCTURES" BY MICHAEL MYLREA, MATT NIELSEN, JUSTIN JOHN, AND MASOUD ABBASZADEH

This chapter describes advances of AI/ML systems to detect cyberphysical anomalies, illustrated with the development of GE's Digital Ghost, a system aimed at improving the security, reliability, and resilience of the power grid in the United States. The design of threat detections for Digital Ghost included machine learning algorithms in combination with deep domain knowledge of the physics for the systems to establish a matrix of credible cyber-attacks, naturally occurring faults, and vulnerabilities.

In addition, the authors review the new challenges coming to make human-machine teams effective against any threat, cyber or physical. The authors review research areas related to the design of this system such as explainable AI, invariant learning, and humble AI as critical techniques for improving the data fusion, trustworthiness, and accuracy of AI-driven technology and its application in empowering human-machine teams.

Humble AI is identified as valuable to marry man and machine, addressing aspects such as how the algorithms can alert the operator of a potential decrease in accuracy or confidence in its threat classification results, if an extrapolation is done into

"Interdependence is a very relevant term in Systems Engineering, AI, and the science of human-machine team work. As hypothesized by the editors, 'the best teams maximize interdependence to communicate information via constructive and destructive interference'."

previously unseen operating regions, etc. Subsequently, an operator would see if Digital Ghost should halt operations or continue but express reduced confidence in its results.

Explainable AI, as a feature of AI-based machines to explain the reasoning underlying their decisions in a way understandable to humans, is identified as a key to develop intuitive and trustworthy explanations for decisions provided by AI algorithms. As pointed out, the most successful human-machine teams will collaborate by employing interfaces containing easy-to- understand visualization techniques. This result is essential for machines to be trusted in making autonomous/semi-autonomous decisions, especially for kinetic platforms that are increasingly autonomous, as well as for safety and other mission-critical applications that determine diagnostics and cyber-physical security.

CHAPTER 14. "CONTEXTUAL EVALUATION OF HUMAN–MACHINE TEAM" BY EUGENE SANTOS JR, CLEMENT NYANHONGO, HIEN NGUYEN, KEUM JOO KIM, AND GREGORY HYDE

In this chapter, the authors explain examples of designing human-machine teams for the domains of healthcare and disaster relief. They highlight the importance of explanations in these hybrid teams to improve efficiency and productivity in complex dynamic environments.

For most human-machine team settings, typical metrics used for end users are insufficient to describe performance, and more explanations are crucial because they help understand a team's operational dynamics and identify the shortcomings that individual agents introduce to the team. These explanations allow performance predictions and quickly identify the shortcomings that individual agents (human or machine) introduce to the team.

One of the key terms proposed is interference, used to capture a team's interactional processes. Interference occurs when the goals of one agent affect the goals of the other agents [15], either in positive or negative ways. Interference is likely to arise due to differences in communication mechanisms, roles, capabilities, adaptiveness, and responsibility between humans and machines.

In order to reflect the underlying agent goals and preferences, in relation to behavior, the authors propose the use of rewards in the framework of inverse reinforcement learning (IRL) using a team's past behavior. The rewards are mapped with high-level behavioral attributes (behA) that are connected to a team's performance metrics. These behA provide insights that will then help to explain a team's performance in relation to agent behaviors.

Finally, authors analyze different compositions of team members that complement each other, with experiments to study the effect of each individual's behA into human-machine team interference. The results suggest that predictions of team attributes reflect actual team behaviors, encouraging further research on the lines presented.

CHAPTER 20. "ENGINEERING CONTEXT FROM THE GROUND UP" BY MICHAEL WOLLOWSKI, LILIN CHEN, XIANGNAN CHEN, YIFAN CUI, JOSEPH KNIERMAN, AND XUSHENG LIU

The authors present a detailed use case to analyze human-machine collaboration, using sensors, speech, and gesture inputs. The problem used to exemplify the process is the collaboration between a person and a Sawyer robot to solve physical block-world assembly problems. The human collaborator defines the problem to be solved and gives instructions to the robot, either step-by-step or at a higher level. It is a modular design, where context is maintained on a shared board to keep the information needed for problem-solving and shared for members of the team.

The physical system contains a camera, a depth sensor (in Kinect V2 for Xbox One), and a laptop microphone. The Kinect and the camera are located in a fixed space, overlooking a table-sized interaction space. The robotic arm has its own camera attached to it, near the gripper. The main information sources and processing modules are:

- Data from sensors are interpreted to determine the locations of objects in the collaboration space, in the framework of the interaction process. Block locations are stored relative to the position of the camera.
- For gesture recognition, pointing gestures of a human collaborator are interpreted by means of utilities provided by the Xbox Kinect V2 software, describing a hand's skeleton to determine the direction and location of the pointing actions. It provides a heuristic value that estimates each block's certainty of being identified by a gesture.
- For Speech-to-Text, it uses the Google Cloud service that receives an audio snippet of the speech input and sends back a string representing the spoken text.
- For text parsing, the Stanford CoreNLP library's dependency parser is used to annotate sentences with both universal dependencies and parts-of-speech tags. This information is stored in a Semantic Graph object by the parser.

The information for processing tasks is represented using the Unstructured Information Processing Architecture (UIMA,

2019) developed by the IBM Watson team. UIMA contains the "Common Analysis System", or CAS. Similar to a blackboard architecture, a CAS object serves to capture information in various stages of refinement. Some examples of text parsed in UIMA are shown, capturing information through software components called annotators, so that new pieces of information are stored for future interactions.

SUMMARY

AI, SE, and human–machine teamwork are linked by interdependencies, a key aspect to be considered in the design of complex systems. The book contains a big sample of the research and development areas which are evolving to integrate the advances in AI and ML technologies in complex and critical systems. New systems engineering methods, processes, and tools must be developed to cover the emerging AI and ML technologies and their new applications in order to make these systems reliable, safe and secure.

These challenges must be addressed to move AI/ML systems forward to operate in real conditions, interact tightly with humans, and meet expectations in complex, dynamic situations. The book shows the way towards developing the next generation of AI/ML systems designed with engineering methods to provide assured cost-benefits while achieving desired effectiveness.

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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.

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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.

FUSION

VENICE | JULY 2024

JOIN US AT THE 27TH INTERNATIONAL CONFERENCE ON INFORMATION FUSION IN VENICE, ITALY

Venice, Italy, will be home to the 27th ISIF FUSION Conference in 2024. Venice was founded over 1,500 years ago on 117 different islands in the middle of the Venetian Lagoon in Northern Italy. This pioneering city was built on water, and water is totally incorporated into the daily life of its inhabitants.

Venice was one of the most powerful European States for several centuries, giving birth to a unique culture and lifestyle. The waters of the lagoon rise and flood the city on a regular basis, complicating efforts to preserve its architecture, which includes Italian, Arabic, Byzantine, and Renaissance forms.

Today Venice is recognized as part of the artistic and architectural heritage of all humanity. Venice and its lagoon were collectively designated as a UNESCO World Heritage Site in 1987. It is renowned nationally and internationally for its charm and its enchanting landscapes. The visitor arriving in Venice is transported into another world, one of incomparable atmosphere and beauty. Churches, museums, and art galleries are present in every corner of the city. Venice is a tourist city par excellence, and over the years has perfected its ability to welcome its visitors.

We look forward to welcoming you to Italy.