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.

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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.

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.

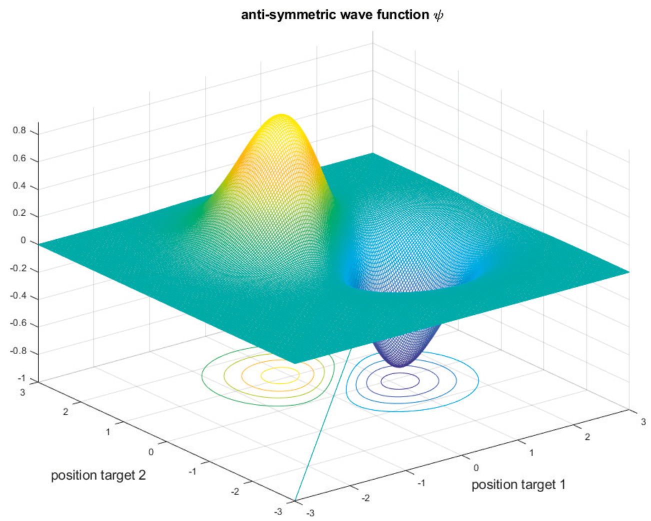
Although the link between mathematical statistics and quantum physics has long been known, the potential of physics-inspired algorithms for data fusion has just begun to be realized.

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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