KIND Synergy Fellow Application

1. Applicant

Name: Rouven Alexander Koch

Current affiliation*:* Department of Applied Physics, Aalto University, 02150 Espoo, Finland

Most significant achievements*:*
The most impactful research of my career is within topics at the intersection of condensed matter theory and generative machine learning (ML), in particular, focused on algorithms to study complex many-body physics. During my PhD research, I designed and developed an innovative new ML algorithm based on generative adversarial networks. I used this algorithm to efficiently speed up complex simulations of novel many-body phenomena [1,2] and, furthermore, I employed the algorithm in an experimental setting to infer Hamiltonians from data [3]. Finally, I coordinated a collaboration between Aalto University and four research groups at TU Delft; two experimental groups and two theory groups. Together, we developed an algorithm to automatically tune state-of-the-art quantum devices based on two different experimental platforms that are designed to implement so-called Kitaev chains [4]. The algorithms that we developed bring together theory and experiments and allow us to learn hidden parameters and control complex quantum systems which is of increasing importance for systems with growing complexity that go beyond traditional methods. Furthermore, I contributed to the machine learning for quantum physics community by co-authoring the book ”Machine Learning in Quantum Sciences” [5].

2. Title of the Project

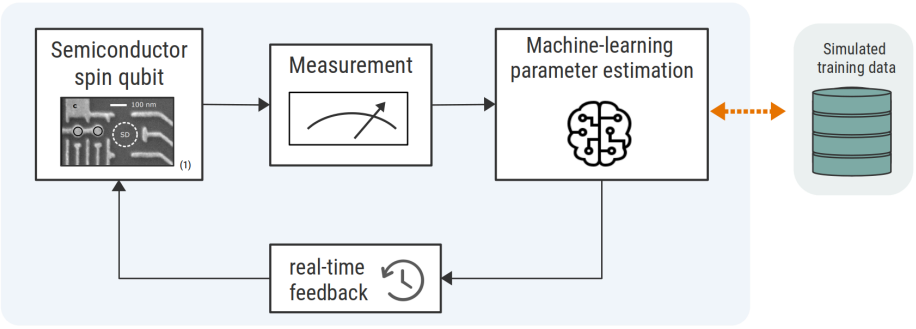
Real-time optimization and feedback for semiconductor spin qubits with artificial intelligence

3. Host groups

- Anasua Chatterjee, QuTech
  website: https://qutech.nl/person/anasua-chatterjee/
- Eliska Greplova, Department of Quantum Nanoscience
  website: https://www.eliskagreplova.com

4. Abstract

This project will improve the control of qubit systems based on semiconductor spin qubits using machine learning algorithms. These qubits are known for their long coherence times and are predicted to be useful in quantum computing and quantum sensing. However, spin qubits are also known to be sensitive to environmental fluctuations and may, therefore, require precise real-time feedback to maintain performance that poses an outstanding scientific challenge. We will tackle this challenge using novel optimization algorithms based on artificial intelligence. Our goal is to develop real-time optimization protocols using theoretical models to control spin qubits in real experiments. With optimal control, we expect to reduce quantum decoherence and maintain continuous calibration of the quantum devices, pushing forward improvements in quantum applications. We will publish these algorithms as open-source packages for wider use in the community. Our work will tackle dynamic qubit control using advanced machine learning and through the successful execution of this project, we will initiate a new paradigm for quantum control methods within the domain of experimental physics.



5. Description of the proposed research

The **general motivation of this project** is to improve the control and optimization of qubit systems which is of immense importance for quantum devices and their applications, including quantum computing and quantum sensing [6,7]. A promising platform for the realization of these quantum devices is semiconductor spin qubits due to their long coherence times and high gate fidelities [8,9,10]. However, current few-qubit prototype quantum processing units (QPUs) are very sensitive to fluctuations in the environment and, therefore, we aim to implement feedback and optimization methods in real time to maintain performance.

The **specific goal** of this research project is to develop novel real-time optimization protocols based on theory models and machine learning algorithms to optimize the control of semiconductor spin qubits. In particular, we will incorporate machine learning-based parameter estimation with real-time feedback techniques for the control of quantum devices. Our goal is to demonstrate adaptive real-time optimization schemes, improving the previous state-of-the-art, to mitigate quantum decoherence, extend lifetimes, and maintain QPU calibration and uptime which ultimately will yield better quantum computing or sensing applications. We aim to publish the optimization algorithms as open-source packages, easy to use, and adaptable to different experimental setups so that the community can benefit from these developments.

Our approach combines Hamiltonian estimation methods with real-time monitoring to perform adaptations of the quantum state of the qubit system in its constantly changing environment. Small changes in gate voltage can affect the fidelity of single and two-qubit gates, as well as the sensitivity to slow and fast varying noise. This project can methodologically be seen as an extension to our previous work, demonstrating the automated tuning of Kitaev chains which also incorporate quantum dots, to the more complex task of dynamical real-time qubit control by applying state-of-the-art ML algorithms to improve current Hamiltonian estimation methods. In our previous works [3,4], we successfully developed and implemented an automated tuning algorithm for experimental realizations of quantum systems by combining ML, theory, and experiments. We have developed a transferable methodology to extract information and automatically tune quantum devices by controlling some of the experimental parameters and, therefore, changing the state of the system. In this project, I will aim to go beyond the simple neural network evaluation of the state of the setup towards optimizing the control of qubits by implementing a similar algorithm that is capable of adaptively changing gate voltages in the environment and state of the qubit system. The requirement for real-time response additionally requires tight integration of the machine-learning algorithm with the experimental control electronics. My background in theory and algorithmic techniques will aid me immensely, as I anticipate a need to bridge the domains of experimental physics and computational quantum control techniques.

6. Host environment

The two host groups have a great synergy for the proposed project by combining the expertise of Prof. Greplova's group in the automated control of quantum devices [11, 12] and Hamiltonian learning protocols for quantum experiments [13] (including a variety of algorithms and ML models) with the expertise of Prof. Chatterjee in quantum control and optimization of (semiconductor) spin qubits and their experimental realizations [14, 8]. In particular, I will build upon the expertise of Prof. Greplova to develop efficient quantum parameter estimation algorithms. However, since it is required that these algorithms can be deployed for real-time control, they must be co-designed along with the experimental techniques [15]. Prof. Chatterjee has previously successfully been part of such co-development [14] and I will build on this knowledge during the project. In Prof. Greplova's group, I will have access to state-of-the-art computational resources on the Delft

Blue cluster as well as the code base developed in her group. In Prof. Chatterjee's lab, a new experimental setup will be set up in the coming months for spin qubit experimental and I will have the support of Prof. Chatterjee's group for the experimental work. The synergy and expertise at KIND lay the foundation for a successful environment to develop novel control algorithms based and direct implementations in experimental setups considering previous successful international collaborations among theory and experimental groups at TU Delft and Aalto University.

7. Benefit to the career of the fellow

1. Benefits for my career: The project will benefit my career in several aspects: first, it allows me to deepen my previous and still ongoing collaborations with groups from TU Delft that I initiated during a research visit in Prof. Greplova's group in 2022 during my Ph.D. The collaborators include the groups of Prof. Greplova, Prof. Kouwenhoven, Prof. Wimmer, and Prof. Goswami. In particular, the interdisciplinary theory-experimental collaborations can benefit a lot from direct interactions and the possibility to visit the labs. Furthermore, the project allows me to start a new collaboration with Prof. Chatterjee where we will focus on the intersection of machine learning, theory, and experiments to study spin qubit systems and develop novel control algorithms that we implement at the Kavli Institute of Nanoscience. Additionally, the extensive expertise in spin qubit arrays at TU Delft will allow me to gain expertise in this front-running quantum computing platform. The proposed project is a great opportunity to transition from my doctoral research on Aalto, where I already focused on direct experimental applications of my (theoretical) research in ML for condensed matter, to the postdoctoral career path after my graduation this summer at Aalto University. TU Delft, and particularly the Kavli Institute of Nanoscience, is the ideal environment to develop myself in the research direction in which I already specialized towards the end of my doctoral research, and, therefore, laying the foundation for a successful academic career.
2. Follow-up research: The proposed project lays the foundation for further collaborations within the research groups of Prof. Greplova and Prof. Chatterjee and has opportunities for natural extensions to the research project. For example, for operating larger quantum devices of spin qubits, new challenges may arise from cross-talk or correlated errors across the device and it will naturally be interesting to extend the algorithms developed here to address these problems. Furthermore, this Synergy Fellowship gives me the chance to continue working with my host groups at the Kavli Institute of Nanoscience, either directly as a postdoc at TU Delft or as a collaborator from a closely related research group.

8. Benefit to the synergy of KIND

This project will initialize a collaboration between the two host groups that have already great synergy in their research directions of quantum devices and computing, particularly in the field of automated tuning and qubit systems both from a theoretical and experimental point of view. Furthermore, this project will stimulate further collaborations and exchange among other researchers and students of each group. Additionally, the precise control of spin qubits may also be interesting for the development of large-scale devices in the QuTech labs of Prof. Veldhorst or Prof. Vandersyper. Additionally, the spin-based sensing device developed in the lab of Prof. van der Sar's lab at the Department of Quantum Nanoscience may also benefit from our control algorithms.
The project is the beginning of a deeply integrated experiment-theory collaboration framework within KIND. At the current technological stage, a certain degree of AI-driven automation is necessary for functionality of the large-scale experiments. Starting to work towards infrastructure where we train and employ staff proficient in both experimental control and computational techniques optimization is essential for successful experiments. This approach goes beyond traditional theory-experiment collaboration. In the individual groups, and my previous work, various components demonstrating the efficacy of ML-based approaches have been shown both for quantum technology (spin qubit tuning and optimization) as well as for condensed matter physics problems (Kitaev chain tuning), among others. However, this class of techniques has a far broader potential in the applied sciences, from imaging, to automatically designing devices, to achieving measurement speedups. Our aim of building an open-source framework that can be utilized and adapted by multiple groups across the Kavli Institute will kick-start a host of activities in this area.

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