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Towards a Quantum Spacecraft Operations Centre

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This article will report on the efforts of the DLR German Space Operations Centre (GSOC[1]) to join two major themes of modern science, namely satellite operations and quantum technologies which culminated in the recently formed Quantum Space Operations Centre (QSOC[2]). This article will present the on-going activities and focus on the problems that quantum computers in a productional environment currently face.

Nomenclature

GSOC	=	German Space Operations Centre
QSOC	=	Quantum Space Operations Centre
NISQ	=	Noisy Intermediate Scale Quantum Device

I. Introduction

Since the first mission AZUR, a lot of experience and knowledge was gathered and continuously incorporated to improve satellite operations, such that today more than a dozen of satellites in low earth and geostationary orbit and the Columbus Module at the ISS are operated at the DLR-GSOC in Oberpfaffenhofen.

Quantum technologies have played an important role in science, research and industrial applications for over 100 years. Everyone is familiar with early examples such as semiconductors, transistors or lasers. The theoretical use of quantum information technologies has been considered since the end of the last millennium, and in recent years quantum computers, as well as quantum communication and quantum sensors, have become a reality in the scientific and industrial landscape.

The operational use of these novel methods of quantum computers is currently still in the medium term (5-15 years until the first quantum computers with a significant number of quantum error-corrected qubits). Until the actual use of quantum computers, due to the exponential speedup in the factorization of large composite numbers by Shor's quantum factorization algorithm, 'Quantum Angst' will spread among all users of classical encryption methods. In the course of these first ground breaking results, which are now almost 30 years old, a number of other quantum algorithms or general applications of quantum technologies have been developed, which cover a wide variety of areas.

Combining these two fields of research feels like a natural step. Looking at the efforts of international companies to advance the construction of quantum computers, it seems essential to start incorporating 'Quantum Technologies in Satellite Operations'. A correspondingly named taskforce was founded 2019 at the GSOC, right before the first proof of quantum supremacy has been demonstrated. Since then numerous projects were initiated, some of them already started.

II. Current Activities

Several quantum algorithms are investigated to be applied in satellite operations. The first field to apply them to is planning problems. Ranging from planning of earth observation, over scheduling ground station contacts to setting up on-call time tables for system engineers. Here, the task is to come up with a conflict free plan given a set of task specific constraints. For earth observations this has to respect onboard memory as well as downlink times, for example. In the case of on-call scheduling, a continuous support for the mission by engineers as well as holiday requests have to be incorporated. Although quite different, depending on the specific setup, these kind of combinatorial optimization problems may take an exponential amount of classical steps towards an optimal solution. Quantum computers offer at least a quadratic speed up for most of the problems. To gather first experiences with the transition to quantum algorithms, we started with the easiest among the given examples, which is on-call planning. It was shown that it is possible to design a Grover-based quantum search algorithm, that is able to solve small scale scheduling tasks. The resulting plan was conflict free, but only a small number of personnel could be scheduled for a few number of days. Since all of these problems fall into the class of combinatorial optimization, also other quantum algorithms like Quantum Approximate Optimization Ansatz seem to be applicable and will be investigated in future projects.

Another challenge is to supervise a spacecraft's health. This is done on a regular basis by system engineers supported by artificial intelligence and machine learning systems. Inspecting satellite telemetry like currents, temperatures, flags, etc is mandatory to identify potential risks to the satellite early enough to react and counteract malicious situations on board. This offers the approach to integrate quantum computers, since quantum machine learning algorithms, although still questionable concerning their real benefits, are applied to identify anomalies. One of the main challenges here is to map classical data onto the quantum computer efficiently which is mandatory for a computational speed-up. To tackle this a project was started to investigate different encoding strategies. Finding a suitable encoding offers the possibility to discriminate sets of telemetry data, for example judging between healthy and anomalous behaviour. This can be done by quantum support vector machine, a type of supervised quantum machine learning algorithms. The latter use labelled training data to judge new test data accordingly into one of two classes.

In addition to quantum computing, the area of quantum communication will of course also become important for satellite operations, which also covers the use of post-quantum cryptography methods. Since DLR currently lacks a satellite in orbit to gain practical experience in distributing quantum keys or entanglement from space, the current focus is on integrating quantum communication means in the ground segment. This encloses the data flow from customers to the control centre, like planning requests in the one direction or delivery of data acquisitions in the other, as well as data links from the control centre to the ground station. For the latter, it shall be demonstrated how to integrate quantum key distribution in a standardized way, sending telecommands and receiving telemetry. As for the very future, one might even think of data from a spacecraft transferred by using quantum teleportation.

As mentioned above, to exploit quantum-assisted computation to its full extend, the data itself needs to be quantum. This touches the realm of quantum sensing and the question, how to record quantum data directly without an intermediate classical state. An upcoming mission will demonstrate a quantum gyromagnetic sensor. GSOC will support the design of this satellite and operate it. The cross expertise in quantum technologies and satellite operations of GSOC employees is a highly demanded skill in this case.

Apart from the applications side, we are participating in projects to improve the actual control of quantum gates on a hardware level (Munich Quantum Valley) and to investigate the implementation of quantum error-correcting codes on dedicated quantum hardware (DLR). Our main contribution here is the explicit implementation of quantum circuits on quantum computer by using quantum control theoretic means. Being given access to real hardware, we can make use of the whole stack of quantum hardware development, error-free (logical) qubits, implementations of error-correcting quantum codes, and optimal control of quantum hardware to implement the encoded qubit operations to push the limits of quantum application development. These efforts are supported by initiatives of the BMWK, the DLR and the Bavarian state. As a side product, we investigated the application of optimal control methods, usually used to drive quantum devices, to optimize satellite attitude steering.

Last but not least, also in project management, the early involvement in project planning and the calculation of operating costs can also be transferred to the operation of quantum technologies thanks to many years of experience with satellite missions and represent considerable potential for cost reduction during the project period.

III. Quantum Computing in Operation

Currently most quantum algorithms are simulated on classical computers since nowadays quantum computers are still way to small and too noisy to really do enough quantum operations until decoherence ruins the calculations. For example, the Spacecraft Quantum On-Call Algorithm needs around 30 error-free qubits to run a quantum circuit containing several thousands of two qubit operations. Both requirements are not met by available quantum hardware. During this time of the so-called NISQ-era of noisy intermediate-scale quantum computers, the focus lies on the embedding of quantum computers in the overall calculation workflow, bearing in mind that most problems will be best solved by quantum and classical co-computing. The strategy is to decompose the task into smaller fragments, solve those by quantum methods and combine the results classically. This hybrid approach yields the flexibility to adapt to growing quantum devices in the future.

Crucial for the seamless integration of the hybrid approach is to provide interfaces between the established classical tools and the newly developed quantum platforms. The definition and creation of these interfaces, an important aspect to which great attention is already paid, also provides the opportunity to define the access to quantum hardware and to operate it in a standardized way. Hereby, in the interface design process scalability and flexibility are of utmost importance to be easily adaptable to the growing size of quantum hardware and to exploit the assets of hybrid systems that make use of the benefits of both worlds at the optimal spot of operation splitting.

This reveals the fact that hybrid computing systems and satellites are quite similar systems. Both are remotely controlled, highly complicated and structured into several supporting subunits, allowing the main payload aka the quantum device, to operate along a given schedule. Standardization approaches apply to satellites and quantum computers alike and concepts from both worlds can be thought of as a way of unifying operations of quantum computers and satellite missions to make use of synergy effects in controlling them. As a consequence, we joined the Standardization initiative of CEN-CENELEC to identify areas in the construction and operation of quantum computers.

IV. The Quantum Spacecraft Operations Centre

All of these projects and activities can be understood as building blocks of a Quantum Spacecraft Operations Centre that bundles these activities within the GSOC and is particularly visible to the outside as a unique initiative of the space organizations. The QSOC will integrate further projects in the future, pool efforts and exploit potential synergies, as well as underlining the public image of quantum technology in space as part of the DLR quantum initiative. A large number of potential partners can be approached, since applications of quantum technologies in space and satellite operation are emerging as a worthwhile field of work: Be it the need to work on a large amount of payload data collected by satellites, e.g. earth observation, climate data or the challenges that arise in operations, e.g. applications in attitude control or improving the accuracy of telemetry data using quantum sensors, as well as the duties in the ground segment, e.g. satellite telemetry analysis or mission planning. All conceivable quantum technologies find a place in the Quantum Spacecraft Operations Centre.

The Quantum Spacecraft Operations Centre (QSOC) ecosystem
Satellites collect data from quantum sensors, e.g. quantum metrological measurement methods to improve acceleration sensors or earth observation data using quantum radar. Furthermore, quantum keys or entangled particle pairs can be distributed from space to other satellites and ground stations or other users. Post-quantum crypto methods or quantum keys or hybrid systems are in turn used to secure the route from customer to satellite and back. Within the QSOC, routine timelines are provided by the planning system and satellite telemetry data is analysed. All calculations are performed by hybrid systems of classical and quantum computers on-site or remotely. Payload data from quantum sensors can be teleported and analysed directly using entanglement. Users can be given computing time or be supplied with quantum keys or entanglement from space. The attitude control of satellites can be optimally controlled using methods from quantum control theory. Quantum control theory is also applied to run the QCs optimally.

Reference:
[1] https://dlr.de/rb
[2] https://qsoc.space