Quantum Annealing for Air Traffic Management
Interim Report, July 2016
Quantum AI Lab, NASA Ames

Aim: To provide an initial assessment of the potential of quantum annealing to attack challenging computational problems in the ATM domain. **Approach:** This assessment will be based on a case study, involving runs on the D-Wave 2X quantum annealer and classical annealing simulations, in which a variety of quantum annealing approaches are developed and compared on benchmark problems derived from a specific real-world ATM problem. **Personnel:** This work is being performed by members of the QuAIL team (Tobias Stollenwerk, Bryan O'Gorman, Salvatore Mandrà, Davide Venturelli and Eleanor G. Rieffel) with expertise in applying quantum annealing to real-world problems, in close collaboration with ATM domain experts (Olga Rodionova, Hok K. Ng and Banavar Sridhar). This work builds on the team's promising prior results in other planning and scheduling domains [1, 2]. **Projected final project outputs:**

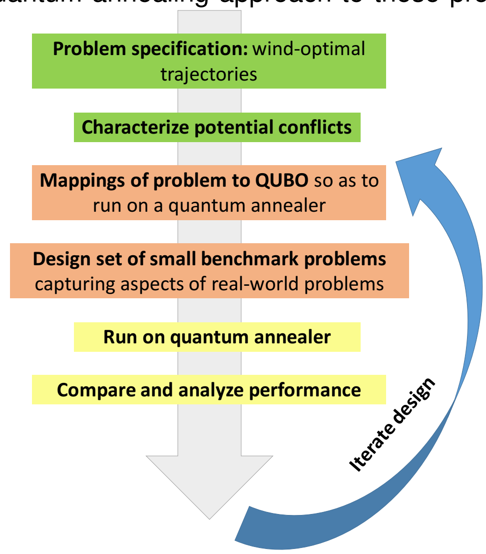
- Programming toolkit to analyze trajectories and potential conflicts
- Mappings of the ATM problem to QUBO
- Implemented mappings on benchmark problems: taking a set of wind-optimal trajectories and outputting a QUBO instance
- Analysis of runs of benchmark instances on the D-Wave 2X quantum annealer
- Report summarizing initial assessment, with recommendations for future research

Results to date (3.5 months)

Summary of completed tasks (3.5 Months):

- Identified specific ATM problem, deconflicting trajectories, as case study
- Devised code to analyze and visualize wind-optimal trajectories
- Identified and characterized all potential conflicts in NAT dataset
- Developed formulations of a simpler version of the problem with only origination delays, amenable being run on a quantum annealer. Write-up available
- Began developing formulations that support manoevers as well as delays
- Identified subsets of data treatable independently, a first step in the design of a set of small benchmark problems

We have identified a specific ATM domain to serve as a case study, namely deconflicting wind-optimal aircraft trajectories. We build on the work of Rodionova et al. [3, 4] who developed a non-quantum approach to this problem. The following graphic shows the main steps in developing a quantum annealing approach to these problems.



Throughout this document, green indicates steps completed in the past 3.5 months, yellow/orange indicate steps to be completed in the next 4 month period, with orange for already partially completed tasks.

We have formulated a basic version of the problem, one that considers only origination delays, in a way that is amenable to quantum computing. Furthermore, we have developed tools to characterize the potential conflicts in order to devise parameterizations and encodings of manoevers in flight so that our approach can support quantum annealing approaches that consider manoevers as well as delays. From these formulations, we have developed multiple mappings to quadratic unconstrained binary optimization (QUBO), the type of problem specification current annealers such as the D-Wave 2X require.

In order to optimize our formulation of the problem for realistic data, we focus on flight data in the North Atlantic oceanic airspace (NAT). Rodionova provided us with wind-optimal trajectories for two consecutive days (July 28^{th}-29^{th} 2012), trajectories on which her state-of-the-art approach has been evaluated. We have already implemented the first step in processing the raw data into useful form: given the trajectories, find the set of potential conflicts. We have also developed code to evaluate the dependencies in the data set, enabling the identification of subsets of the data that can be treated independently, a step toward the design of suitably small benchmark sets that will fit on the D-Wave 2X prototype quantum annealer in spite of its limitations in terms of number of qubits and connectivity.

Proposed next steps (4 months)

We need to finalize the mappings to QUBO for the full problem, supporting both origination delays and in-flight manoevers. We will design benchmark small instances, either well-chosen subsets of or constructed instances based on NAT dataset structures. Before analyzing the performance of quantum annealing on our formulation of the problem, we first analyze the formulation itself by comparing solutions from classical QUBO solvers to those from extant methods. Then, we run these benchmark instances on the D-Wave 2X, a state-of-the-art quantum annealer, and also run classical annealing methods on the Pleiades supercomputer to support larger size problem, enabling an assessment of the scalability of our methods. We compare the diversity of solutions returned, as well as the quality of solutions returned, since in a wide range of settings, practitioners are interested in a *diversity* of solutions from which a human can select based on unformalized criteria.

Next steps (4 months):

- Develop a variety of mappings to QUBO of the problem with maneuvers.
- Design a set of benchmark ATM problems based on NAT data.
- Run state-of-art classical QUBO solvers and the D-Wave 2X quantum annealer on the benchmark set, and analyze the performance.
- Feedback results from these initial runs into proplem parameters and encodings. Design more advanced set of quantum annealing or hybrid quantum-classical approaches to these problems

Request: 150K for $\sim$ 1.5 WYE for 4 months

Task/Milestone	Performance Metric	Expected completion from start of project
Implement code to identify, characterize, and visualize potential conflicts for different thresholds	Correct and efficient characterization of potential conflicts. Usefulness in formulating a model of potential maneuvers	2 months
Mappings of ATM problem, with origination delays only, to QUBO	Resources required (number of physical qubits)	3 months
Mappings of ATM problem to QUBO, incorporating maneuvers	Resources required (number of physical qubits)	5 months
Design a set of benchmark ATM problems derived from NAT dataset	Extent problems capture of most challenging aspects in small problems	6.5 months
Initial runs and analysis of performance of D-Wave 2X on benchmark ensemble	Quality and diversity of solutions. Scaling of expected time to solution vs. size	8 months
Iterating on QUBO design and QA parameaters, an peform further runs and analysis of performance	Quality and diversity of solutions. Scaling of expected time to solution vs. size	10 months
Written report comparing the approaches developed, providing an initial assessment of the potential of quantum annealing for attacking ATM problems based on the case study, and making recommendations for future work	Thoroughness of case study and grounding of recommendations	12 months

References

[1] Eleanor G Rieffel, Davide Venturelli, Bryan O'Gorman, Minh B Do, Elicia M Prystay, and Vadim N Smelyanskiy. A case study in programming a quantum annealer for hard operational planning problems. *Quantum Information Processing*, 14(1):1–36, 2015.

[2] Davide Venturelli, Dominic JJ Marchand, and Galo Rojo. Quantum annealing implementation of job-shop scheduling. *arXiv preprint arXiv:1506.08479*, 2015.

[3] Olga Rodionova, Daniel Delahaye, Banavar Sridhar, and Hok K Ng. Deconflicting wind-optimal aircraft trajectories in north atlantic oceanic airspace. In *AEGATS '16, Advanced Aircraft Efficiency in a Global Air Transport System*, 2016.

[4] Olga Rodionova. *Aircraft trajectory optimization in North Atlantic oceanic airspace*. PhD thesis, Université de Toulouse, Paul Sabatier, 2015.