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with HP Quantum Information Processing Group

Systems
Engineering &
Assessment Ltd

Beckington Castle
PO Box 800
Frome BA11 6TB UK
tel: +44 (0) 1373 852 000
fax: +44 (0) 1373 831 133

email: info@sea.co.uk
web: www.sea.co.uk

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Prepared by .... David Summers & Tim Spiller

Approved by .... Technical Director, Space Systems Division

Authorised by .... Project Manager

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1 INTRODUCTION

1.1 SCOPE

This document is the executive summary for the ESA funded study (ESA/ESTEC Contract 17803/03/NL/LvH) into a Theoretical Evaluation of Quantum Information Processing.

Systems Engineering and Assessment Ltd and Hewlett Packard Laboratories at Bristol, UK have performed the study. SEA brought the space heritage to the project whilst the HP Labs brought the Quantum Information Processing Experience.

The aim of this study has been:

WP1: Review the current status of Quantum Information Processing

WP2: Review and assess the potential space applications for QIP

WP3: Review the QIP technologies, and the potential impact of the space environment

WP4: Define potential Proof-of-Concept Experiments and identify an experiment for further study

WP5: To perform the preliminary design of the identified experiment

This executive summary covers the work performed in the above five work packages, and these are covered in the following sections.

1.2 REFERENCE DOCUMENTS

[RD1] Theoretical Evaluation of Quantum Information Processing, Statement of Work, EMA/03-010/QIP

[RD2] Technical Note 1: Review of Basics and Principles of Quantum Information Processing. Tim Spiller, QIP-HP-1.

[RD3] Review and Assessment of Quantum Information Processing for Space Applications. David Summers, QIP-SEA-1, SEA/04/TN/4553.

[RD4] Quantum Information Processing Technologies Assessment. Tim Spiller and the HP team, QIP-HP-2.

[RD5] WP4 - Definition and Selection of Proof-of-Concept Experiments. David Summers, QIP-SEA-2, SEA/04/TN/4636.

[RD6] WP5 - Preliminary Design of a Entangled Atomic Interferometer Experiment. David Summers, QIP-SEA-3, SEA/04/TN/4660.

[RD7] Final Report of the Theoretical Evaluation of Quantum Information Processing Study, David Summers, Tim Spiller, & the HP team, QIP-SEA-4, SEA/04/TR/4670.

[RD8] HYPER: A Potential ESA Flexi-Mission In The Fundamental Physics Domain: Article. G. Bagnasco and S. Airey, http://sci2.esa.int/hyper/docs/iaf_2001_hyper.pdf

2 WP1: REVIEW OF BASICS AND PRINCIPLES OF QUANTUM INFORMATION PROCESSING

Quantum information processing (QIP) is a new and rapidly developing research area, which has significant potential for wholly new technologies in the future, based on the processing, storage and communication of information according to quantum laws. For QIP, the important features of quantum theory are: (a) Superposition: Systems of quantum bits (qubits) – the quantum generalisation of conventional data bits – can occupy many states and so run many processes at the same time; (b) Entanglement: Separated qubits can have stronger correlations than any permitted by classical physics; (c) Measurement: Measuring a system of qubits realises just one of the many possible outputs, and projects a superposition state into just one.

There are basically two facets to QIP – hardware and software – just as with conventional IT. Both of these facets have been reviewed in detail, from the perspective of the current state of play of QIP research, but also with consideration of specific applications and issues for space.

With regard to software and applications, what can be done depends on the number of qubits available for QIP.

(i) Useful applications exist for small numbers of qubits. As such systems can be simulated with conventional computers, the quantum advantage basically arises through using distributed entanglement, and so relates to quantum communication, or arises by using entanglement to enhance metrology. With regard to communication, few-qubit QIP enables teleportation, dense coding of information, entanglement distillation (providing an improved resource), error correction (keeping a memory qubit coherent for longer) and quantum repetition (which can extend the useful operating distances of quantum communication). With respect to metrology, using entangled qubits enables measurement and sensing to be performed with more accuracy than could be achieved with the same un-entangled resources, taking interferometry past the shot noise limit. Applications include frequency standards, gyroscopes, lithography and the sensing of magnetic fields, electric charge or weak forces (small displacements).

(ii) A few tens of qubits gives a QIP system of sufficient complexity that it cannot be conventionally simulated. Such a system could perform general simulations of quantum systems beyond what is possible today, which could have widespread research applications. Searching through a quantum database demonstrates a square root speed-up compared to conventional searching (Grover's algorithm). This could have use with as little as ~100 qubits.

(iii) QIP systems with a few thousand qubits or more – quantum computers – could significantly speed up (exponentially reduce the time) for certain mathematical tasks such as factoring large composite integers or solving the discrete log problem (Shor's algorithm). Such a quantum computer would break much of the current "secure" communication technology. Shor's and all the related algorithms are based on a quantum Fourier transform (QFT) – quantum superposition enables interference to solve the tasks with a single computation and measurement. The nature of quantum measurement means that quantum computing does not speed up general number crunching – it is only possible to output a single answer (and not, for example, a complete FFT) with one run.

3 WP2: REVIEW AND ASSESSMENT OF QUANTUM INFORMATION PROCESSING FOR SPACE APPLICATIONS

As reviewed in [RD2] the primary areas where QIP has received press and research attention is for applications where the quantum processing requires reduced resources over classical computing. The primary reason for this ability to use decreased resources is due to qubits ability to store entangled information. This means that in a quantum sense qubits contain additional information over classical bits. However when the qubits are measured, which converts the information into a classical form, only the same numbers of bits as the classical situation are recoverable. To put this another way, whilst the power of quantum processing is due to the ability to tightly pack information into a quantum system, the resultant system can only answer a reduced set of classical questions.

This limitation to quantum processing means that the study has not been able to identify a good candidate space application that utilises the two dominant resource-reducing algorithms:

- Grover's search algorithm
- Quantum Fourier Transform

The space applications considered covered the typical generic space applications that today require the highest computational resources:

- Phased Arrays
- Synthetic Thinned Aperture Radiometer
- Synthetic Aperture Radar
- Star Sensor matching algorithm

However the main difficulty was that there are currently only limited quantum computing algorithms that require reduced resources, and these specific algorithms are not suited to current space applications. The current scarcity of quantum algorithms is more a comment on the lack of hardware on which to implement them. It is not until a true quantum computer is built that rapid development on the algorithm front can be expected, however this will likely then bring space applications.

Away from reduced resource algorithms one area of QIP which did offer genuine space application was the area of metrology, in particular QIP enhanced interferometry. By entangling the quanta used in an interferometer the interference fringe spacing is reduced. This means that for situations where small changes need to be measured enhancements can be made. The most apt use is in Sagnac interferometers:

- Optical gyroscopes: either increased resolution, or decreased size, can be achieved without altering the optical frequency.
- Atomic gyroscopes: such as have been suggested for use on the HYPER mission [RD8].

Also considered were Quantum Teleportation, Quantum Dense Coding, and Quantum Memory. The first two are closely related to quantum communication, whilst the latter has no obvious space application.

4 WP3: TECHNOLOGIES ASSESSMENT

A great many possibilities have been proposed for qubits and thus the building blocks of QIP hardware. In order for them to be genuine candidates, they have to satisfy the DiVincenzo criteria.

(i) A collection of well-characterised qubits is needed.
(ii) Preparation of known initial states for the qubits, those involved in the actual processing or communication plus those ancilla qubits used for error correction or purification, must be possible.
(iii) The quantum coherence of the system(s) must be maintained to a high degree during the evolution, or quantum processing, stage.
(iv) The unitary quantum evolution required by the algorithm, application or protocol must be physically realisable with the chosen system of qubits.
(v) High fidelity quantum measurements on specific qubits must be possible, in order to readout the result of the process or computation.
(vi) The capability to interconvert stationary (processing or memory) qubits and flying (communication) qubits must exist.
(vii) It must be possible to transmit flying qubits coherently between specified locations.

These demands are very tough indeed. State of the art today is that few-qubit processors exist – quantum gates have been performed with some candidates, and simple algorithms or applications realised with others. The main candidates and their experimental status with regard to the DiVincenzo criteria are summarised in the table. The detailed reports of this study contain assessment of space issues for the various hardware candidates.

Probably the most relevant space issue for QIP hardware is the nature of the environment. As laid out in the DiVincenzo criterion (iii), a QIP system has to remain coherent for the duration of the processing, so the effects of a space environment must not destroy this coherence. The best route to scalable QIP in earth-based laboratories has yet to be identified, so it is basically premature to try and judge which of these candidate technologies might be best for space. Given this, and in addition the question of what a many-qubit processor might actually be used for in space, it seems that the focus on initial applications and experiments should be directed at the few- or relatively few-qubit level.

With respect to such small scale QIP, probably the most relevant approach is optical, for a number of reasons: (a) Optical qubits (or states) are preferred for communication, so improvements through direct optical processing avoid interconversion. (b) Few qubit QIP could improve metrology and if this is based on some form of interferometry, optical qubits are well-suited. Specifically for metrology, QIP enhancement of atomic interferometry should also be considered. (c) Optical qubits are generally robust against electromagnetic noise, and do not require low temperatures. The additional decoherence sources in space should not be a problem. (d) Detectors and sources should perform in a space environment, and if non-linear components can be made very small and functional on earth, they should also function in space. (e) Whilst not negligible, the physical bulk of supporting hardware for optical QIP seems to be as good as for other QIP hardware approaches.

There appears to be a solid case for focussing on optical QIP as potentially the most relevant for space, at least over the next few years while experiments on all forms of QIP continue on earth. Specifically for metrology, improvement with atomic QIP should also be considered.

QIP-SEA-5

Approach	Qubit	Preparation	Decoherence	Gates	Measurement	What has been done?
Linear optics	Photon polarization or dual rail	Photons from down-conversion	Photon loss in fibres	Photon bunching, measurement	Photo-detectors	CNOT gate between two qubits
Non-linear optics	Photon polarization or dual rail	Photons from down-conversion	Photon loss in fibres, dephasing in atomic systems	Photons interact through atomic systems	Photo-detectors	EIT seen in certain atomic systems for classical fields
Continuous variables	Qunat encoded in quadratures of coherent light pulse	Weak coherent light source or vacuum	Photon loss in fibres	Non-linear medium giving Hamiltonians polynomial in quadrature operators	Homodyne or heterodyne detection	Teleportation of a continuous variable
Ions in traps	Energy levels of ion	Optical pumping and laser cooling	Fluctuating fields, level lifetimes	Collective vibrations and external lasers	Resonance fluorescence	Deutsch-Jozsa algorithm and teleportation
Neutral atoms in optical lattices	Energy levels or motional states of atom	Optical pumping and laser cooling	Fluctuating fields, level lifetimes	Dipole-dipole coupling or collisions	Resonance fluorescence	Mott transition loading of a lattice
Rydberg atoms	Highly excited states of atom, Fock states of microwave field	Chopping and filtering of atomic beam, cooling cavity	Level lifetimes, finite cavity quality factor	Natural atom-cavity interaction	Selective ionization of atoms	Three-qubit GHZ entanglement
Semiconductor charge qubits	Electron in a double quantum dot	Cooling so $kT<<\Delta E$	External electric field noise	External electric and magnetic fields and Coulomb	SET or point contact electrometer	Coherent oscillation of one charge qubit
Semiconductor spin qubits	Electron or nuclear spin	Cooling so $kT<<\Delta E$	External magnetic field noise	External electric and magnetic fields and Exchange	Convert charge to spin, then as above	Coherent oscillation of one spin qubit
Superconducting charge qubits	Charge on a grain/capacitor	Cooling so $kT<<\Delta E$	External electric field noise	External fields and capacitive, inductive or Josephson coupling	SET or point contact electrometer	Coherent oscillation of one and two qubits, and CNOT gate
Superconducting flux qubits	Quantized flux in an inductor	Cooling so $kT<<\Delta E$	External magnetic field noise	External fields and capacitive, inductive or Josephson coupling	SQUID magnetometer	Coherent oscillation of one qubit
Electrons on liquid helium	Energy levels of confined electron	Cooling so $kT<<\Delta E$	External field noise and ripplons	External fields and Coulomb interaction	Selective ionization or SET	Coherent interaction of electrons with microwaves

Table 4-1. Summary of the technologies that have experimentally demonstrated QIP techniques.

5 WP4: DEFINITION AND SELECTION OF PROOF-OF-CONCEPT EXPERIMENTS

The experiments considered under WP4 had their origins in WP2 – Space applications ([RD3] and §3) and WP3 – Technologies Assessment ([RD4] and §4).

For specific space application the current status of QIP technology is such that it is clear that any technology will require ground based bread boarding before a mission. The two primary applications considered were QIP enhancements to optical and atomic interferometry. The physics underlying enhancements to optical interferometers have already been demonstrated (see references 8,11 and 12 of [RD5]) however for this to be a useful technique the following improvements will be necessary, and form a possible experiment:

- A route to entangling multiple photons. Most current experiments only entangle a pair of photons; although the most recent experiments have entangled three and four photons. These in principle bring between a factor of $\sqrt{2}$ and 2 improvement over classical interferometers.
- The current experiments only manage to entangle a small fraction of the photons in the experiment. Whilst this is sufficient for proving the principle behind improvement, it does not lead to an improvement over the level that could be achieved due to shot noise reduction with the larger signal of non-entangled photons.

On the atomic metrology front there is currently no activity on the enhancements that can be made to atomic interferometers from using entangled atoms. However entanglement of atoms has been shown in Bose-Einstein condensates. Demonstrating that these entangled atoms can be used in an interferometric measurement becomes another possible experiment.

From WP3 the qualification of QIP technologies for space suggests possible experiments. Specifically can technologies be created that will function in the environment of space? Although many experiments can be considered, none can be considered apt at this juncture. This is due to the current rate of evolution of QIP technologies. None of the current technologies can yet be considered mature; each is in a rapid rate of change. This means that testing of current hardware to typical space environmental conditions may tell us nothing of the susceptibility of eventual hardware solutions. On the other hand the current experiments are actively investigating the dependence of qubit coherence times on environmental effects, these results will already bring insight into the possible effects of the space environment. [RD5] did however identify the typical generic environmental effects that will affect specific QIP hardware developments.

Finally WP4 selected the atomic metrology experiment for further study in WP5. The primary reason for this is the applicability of this technology to the planned ESA HYPER mission in the 5 to 10 year timeframe [RD8].

6 WP5: PRELIMINARY DESIGN OF EXPERIMENT

The experiment identified for further study during WP4 was a ground demonstration of the possible improvements to an atomic interferometer from using entangled atomic states.

No definitive experiment can be designed at this stage due to the cutting edge nature of the technology. However two possible routes have been identified as being promising:

- **Methods derived from Optical heritage**

  Entanglement of photons in an optical interferometer has been observed by several groups. The critical parts of these experiments are:

  - Production of photons with overlapping wave functions:
    - Parametric down conversion
    - Fast switching of equal time space photons, such that the equal time spacing converts into overlapping wave functions
  - The bunching of photons with overlapping wave functions at a beam splitter, to split entangled photons down different paths.

  The fast switching and beam splitter techniques can possibly be adapted to atomic interferometry and give one possible method.

- **Bose-Einstein condensate initial states**

  Atomic Bose-Einstein condensates have been created via laser cooling. These states consist of atoms with spatially overlapping wave functions. Such are the states that if they can be coherently split to travel the two arms of an interferometer will give the entanglement enhancements.

  Two questions arise over this direction. Firstly can a Bose-Einstein condensate be coherently split? Secondly can a Bose-Einstein condensate be prepared with a state with the required definition for atomic interferometry, *e.g.* can the exact number of atoms in the condensate be controlled?

The proposed experiment would be expected to have four different phases:

- Task 1: Theoretical Study and Definition, where the possible methods of entanglement are studied, the best candidate identified, and the experiment designed.
- Task 2: Experiment Build, where the experiment and associated test equipment is built.
- Task 3: Experiment Test and Analysis.
- Task 4: Proposals for the future development.

7 CONCLUSIONS

Quantum Information Processing is one of the most exciting and rapidly moving areas of physics today. In the last handful of years rapid progress has been made on both an algorithmic and experimental front.

On the software front several algorithms have been developed that show a clear advantage over the classical analogue, the main two being:

- Quantum Fourier Transform: A quantum version of the Fast Fourier Transform algorithm that is the backbone to many quantum algorithms such as Shor's factoring algorithm.
- Gover's Search Algorithm: This searches a quantum database with a square root speed up over classical searches.

Both of these algorithms gain their speed advantage from QIP's ability to squeeze more information into a few qubits via entanglement. This however turns out to be one of the main difficulties of these algorithms; the process of setting up the qubits is a classical process and the resources to do this dominate. Also only limited information can be extracted from the qubits. Hence all classical algorithms which require large amounts of output typically show no quantum advantage. Speed up can occur when very limited data output solves the problem.

This limits the current applicability of QIP algorithms to space applications, such that the only clearly identified area where a clear quantum advantage can be utilised by a space application is in interferometers where quantum metrology enhances the interferometer resolution over the classical shot noise limit. This is most relevant for the Atomic Sagnac Unit for the proposed ESA HYPER mission.

On the experimental front several technologies have demonstrated facets of the requirements of QIP (summarised in the DiVincenzo criteria):

- Optical based qubits: Good coherence and CNOT demonstrated.
- Semiconductor qubits: Decoherence a problem, but ultimately scalable.
- Ion and atom traps: Good for demonstration, scalability difficult.
- Superconducting charge, spin and flux qubits.

The rapid progress being made on each of these areas is very encouraging. However as none of the technologies can yet be considered mature, this means that only generic comments can be made on the effect of the space environment.

The area where the first Quantum-Information-Processing technology is likely to find a space application is a few qubit, quantum metrology techniques. The technology to date has only been shown optically, however atomic interferometry also seems feasible.

This latter suggestion is the area the study has proposed further study: A ground demonstration of the enhancements available to an atomic interferometer from entangled atoms. There seem two ways such an experiment could be pursued:

- Atomic versions of the optical technology for creating overlapping wave functions and entanglement from a beam splitter.
- Projection and entanglement of atomic Bose-Einstein condensates.