

ΙΝΣΡΛΟΕ



Capgemini Sinvent

QUANTUM MAGNETOMETERS AS SENSORS IN SMALL SATELLITE MISSIONS

Mark Chang [Capgemini] Simon Jordan [Cambridge Consultants] Tony Holt [In-Space Missions]

PURPOSE

SKILLS **COLLABORATION**

HUMANS BEYOND EARTH SUPPLY CHAIN

IMAGERY

Cleaning space debris

More satellite capabilities

Secure communication

Space is essential to the Alliance's capabilities. NATO's fostering of cooperation with industry opens the opportunity to rapidly develop quantum technology-based space systems.

SCIENCE

Orbital servicing and manufacturing Position Navigation timing

SMALL SATELLITES FOR DEFENCE

Small satellites are becoming increasingly important in the field of defence. Overall, more than 6,000 small satellites, ranging from a few kilogrammes up to 500 kg have been launched since 2000 for civil, exploratory, and military reasons.

They offer several advantages over terrestrial capabilities e.g., improved situational awareness, enhanced communication capabilities, and increased resilience, usually provided from low Earth orbit, that is up to 2000 km altitude.

Theyoffer

Shorter Development Time Rapid Refresh and Technology Upgrade Increased Training Opportunities and Process Improvement Lower Cost Manufacturing at Scale



HOW SATELLITE ATTITUDE DETERMINATION WORKS

Attitude determination = where am I pointing?

- (A) Use two reference points, like stars, the sun, the horizon, etc.
- (B) Upload GNSS data from the ground station.
- (C) Use the magnetic field + Inertial measurement unit.

High end solution:star trHeritage solution:Inertia

star trackers / sun sensors Inertial Measurement _____

Smallest potential SWaP-C solution:

Magnetometer 🔨





012-12-3010-12-11593_pX.fts		: done, solved (0.9 s)	
age: 2 s ctr_s: 5 [nc] ctr_f: 1759 lat: -77.04* lst: 13.89 hrs	mean: 1866.8 noise: 8.9 num_sat: 0 gain: -0.9 dB	ra: 230 dec: -46 az: 29.0 el: 57.1 hroll: -1.2	1.31* match: 10 of 10 .00° pt error: 1.86° .03* fit error: 0.60 px .73* plate: 9.517° .0* mexp: 68 ms













HERITAGE MAGNETOMETERS

Fluxgate Magnetometer



Saddle coil

Photodiode

Driving

electronics

Macroscopic

cell (~32 cm3]

Miniature cell

(~0.1 cm³)

h)

LC Polarizatio

rotator

1083

nm laser

HF discharge

RF signal

Larmor excitation signal frequency (fL)



Scalar Helium Magnetometer

Vector Helium Magnetometer



In principle these are all variations on a bar magnet class compass.



NATO IST-SET-198 | October 2023

QUANTUM MAGNETOMETERS

Atomic vapour cell & Spin Exchange Relaxation Free (SERF) magnetometers

Alkali-vapour magnetometers are extra sensitive magnetic field measurement devices.

An alkali-vapor magnetometer polarises a vapour of alkali-metal atoms, (potassium, rubidium, or caesium) inside a glass cell using a circularly-polarised "pump" laser beam.

Spinning atoms have a magnetic moment, with north and south magnetic poles, so an outside magnetic field will tilt the axis of spin and cause it to precess like a spinning top that's been pushed off the vertical.

Changes in the outside field's strength or direction can be detected using a probe laser to repeatedly measure the vapour's average spin orientation.

The fundamental sensitivity of the measurement depends on:

- the number of atoms in the sample
- the spin relaxation time of the polarised atoms.

Spin relaxation is the loss of polarisation, the return of the population of atoms to random orientations, which happens faster as atoms collide with other atoms, or if the external magnetic field varies.

SERF cells are modified (with buffer gases or coatings) to minimise spin relaxation.

detector

probe laser.

atom

oumo



QUANTUM MAGNETOMETERS

Atomic Defect

Optical detection of magnetic resonance through the infrared absorption (IR-ODMR) of the Nitrogen-Vacancy centre in diamond (NV centre).

The NV centre is a point defect in the lattice of the diamond which is sensitive to magnetic fields and can be read out optically.

The method is based on excitations of NV centres in a diamond sample using a green laser (532 nm) while a microwave field is applied in parallel. By sweeping the microwave frequency around the vicinity of the zero-field splitting of the ground state of the NV centres, their spectral response can be probed.

At resonance, the absorption of the IR beam at 1042 nm occurs, and the detected laser intensity at the output of the diamond is minimal.









(a) NV ensemble, excited by 532-nm laser pulses.
Long-pass-filtered fluorescence is collected with part of the exciting light on a balanced detector.
Microwave (MW) pulses are used for NV-spin manipulation.

(b)

- (b) NV-energy-level scheme: Manipulation of electron spin in a triplet ground state. Spin-statedependent fluorescence allows readout of the spin state.
- (c) Fluorescence collection with parabolic collector (simulation results).



LABORATORY COTSQUANTUM MAGNETOMETER



Frequency stabilised laser – 780nm (same wavelength as CD burner)





Laser is tuned to D-line of alkali metal (shown here for sodium). This excites the atom into a magnetically sensitive state. The magnetic field makes it oscillate (Larmor precession), we detect this optically. This frequency is proportional to the total magnetic field with extreme precision. This allows measurement of tiny (0.0001nT) magnetic fields







OUR ONE-STOP-SHOP COLLABORATION



Client Research & Lab Programs

WHAT IN-SPACE MISSIONS IS PROUD TO DO



ΛCE

I N

S

Ρ

What we have & what we can do (hosted payloads or dedicated satellite)

SDR HR EO Build Phase SDR Ka-band MR EO LEO-LEO ISL (3) SDR (4) MR EO TESTING INTEGRATION + PAYLOAD TESTED X-Band Payload SYSTEM TEST AND DELIVERED Downlink TO IN-SPACE. (AES256) PAYLOAD INTEGRATED INTO SATELLITE; END-X-Band Payload TO-END AND S-Band TT&C (AES256 & Tasks / Downlink ENVIRONMENTAL (AES256/Auth) HMAC (u/l)) TESTING PERFORMED KSAT/LEA BAE GS (2)LEAF/KSA GSN Great Baddow GSN 1) SUPPORT BUILD PAYLOAD Spacecraft & Mission IN-SPACE SUPPORT Operations THROUGHOUT CUSTOMER DESIGN AND TEST PAYLOAD DESIGN AND BUILD ΙΝ Σ Ρ Λ C Ε **Customer Portal**

IN-SPACE MISSIONS DIGITAL OFFERING





INFORMATION

Exploit our rich archive of geometric & radiometric corrected EO, SAR and RF data, or utilise our tailored analytics products that are continually updated with data from our In-Space Digital Live system.

SIMULATION

Develop your applications in a simulated environment that is fully representative of the operational In-Space Digital Live system configuration.

DATA

Task the In-Space Digital Live system to deliver timely geolocated raw or processed EO, SAR and RF data to further your application development

ORBIT

Validate, upload and execute your application on the live In-Space Digital Live system with the full support of our service delivery team

CAPGEMINI'S CREDENTIALS

OUR QUANTUM TECHNOLOGY AREAS OF EXPERTISE



- Material science, Drug discovery
- Risk modeling & Operational optimization
- Machine learning
- IBM-Q Hub and Broad Capgemini analytics expertise

QUANTUM-SAFE COMMUNICATION

- World-class quantum communication labs in Portugal and Cambridge, UK
- Post-quantum security
- Quantum key distribution
- Quantum internet applications for confidentiality, access control, and consensus protocols

QUANTUM SENSING

- Positioning, timing & navigation
- Radar technologies
- Earth observation
- Strong engineering expertise and laboratory at Cambridge Consultants

CAPGEMINI'S QUANTUM LAB – THE VALUE ADD

Domain experts (Space services, Life sciences, ...)





Technological experts (Engineering, optimization, simulation, machine learning ...)





Facilities in Cambridge & Portugal

30+ engineers from across Capgemini footprint

OUR USP

- End to end implementation
- Turning theory into business bridging the gap between research and use cases
- One stop shop for all quantum
- Flexibility in exploration
- Ability to scale

Tito-so heref 'Inter'/A.csa, ...html5reaetheref 'Inter'/A.csa, ...html5reaetaddwarnen of 2009+csa, ...pop.pc.asa, ...2039-csa, ...style.progressbare.csa, ...20 addwarnen of addwarnen bergened.ct.UhuhYdrvH.csa'/sheref in the sar's so heref in the sar so heref in t

ssheet to _____dtyle.ie_fix_css*/>

esheet* href='/cas/specific/frontpage/A.index.css.q2039.pagespeed.cf.Jvypn1Gp-6.css*/> *application/Id+ison*>

> : "http://schema.org", Organization", "eopleimages", "//peopleimages.com", I "https://www.facebook.com/ tter.com/yuriarcurs",

А.1.0.0 "торой страниций стран

agency, library, gallery "/> olis, stock photography, stock image, pictures, images, photographs, roy ice-width"/> p.g.used png"/> c.b.agenciation, string inset in the "vimitsactik xml" title="Peoplemages.com"/>

> скот тики // лицинальнать селини рицани, радинать на и на строй kase, Universitani sea - Эларану, и радини и , сазь, это ил саз. Доло дой кази, радора сазь "Кароланская, втуй в радинать ил сазь Мос дой КаЮИLE. сазь радинариев ct. Univity drvik, cas'/>

> > 47.843.80, 81.8478324.*3944.1

ret="/cas/style.ie7_fix.cas"/>

dipat></setipt>

ml5shiv.googlecode.com/svn/trunk/html5.js*>-</script> ie_fixes.js*></script>

rtrideleasigehable*:true, "dktab_realplexor_urt":"http:///rp.peopleimages.com", "dkta

-

"keywords" contents" and of any mening as you weening busier, mar and an other projects, set the works a top setting photo contention at photes you ca "keywords" contents" stock photo-stock image, pictures, image, photographe, rovally the analysis, palary "to

> ewport* content=*width=device=width*/> _src* heet=*/images/site/logo_squared_png*/>

** type="application/opensearchdescription+xml* href="/xml/search.xml* title="PeopleImages.com", con.lco?v=2* rel="shortout toon"/> ewankinger.thereful_timeges.idli & ans.com.exect.org.exect.org.idl.cfu..ct0.org*/>

error ydrauti (skyan, skyriliganky, litxary, gallwy')> ustriamin sav.4009+csa., popus csa., q2009+csa., style progressbara.csa.,q2009+csa., specific,., bannera., style csa+3rdparty., jquery-ul., csa., amoothne wielmages.com/y * stylesbares*/treat/vsavistyle.je.jik.csa*/>

> •*styleaheet* hvet=*/csa/style.ie_fix.csa*/> Ø #deksyepi&Rest_benetety/outpla/kasead/aparty...jquery-ui,_csa.._amoothnesa...jq

esheet* href="/css/specific/frontpage/A.index.css.q2039.pagespeed.ct.Jvypn10p-6.css*/>

"http://schema.org", brganization", vopteimages", {"bttps://www.facebook.com/yurlar tits.com/yurlarure", tits.com/yurlarure", tits.com/yurlaroure", opcodelma.org.opteimages",

CAPGEMINI'S QUANTUM LAB RESEARCH INTO MAGNETOMETRY

NEXT-GENERATION QUANTUM-ENABLED MAGNETIC SENSING WITH THE UNIVERSITY OF STRATHCLYDE





Curtamenter Curta

Challenges

To create a magnetometer that detects the magnetic field using optical rotation of the plane of polarization of a laser in a rubidium vapor

Key elements

- Experimental setup of quantum sensor based on a rubidium vapor
- Control of laser frequency
- Control of background magnetic field
- Signal processing, and filtering out noise

Success

- around x100 sensitivity improvement over a conventional sensor
- Identified use cases for medical imaging and navigation
- Market opportunity identification

Tistopo et al. Market VA.cea., http://www.cea.action

lesheef lesheef lesheef* hrete*/css/style.le7_fix.css*/>

* sheet* href="/csa/specific/frontpage/A.index.css,q2039.pagespeed.cf.Jvypn1Gp=6.css*/> *application/id+ison">

> : * http://schema.org", Organization*, *eopleimages*, *//peopleimages.com*, f *https://www.facebook.com/ tter.com/yuriarcurs*,

a test integes for your websits, poster flyer and all other projects. Our advecting poster flyer and all other projects. Our output of the second second

Versity for the summarization of the second programmed on AWL d30 of locon². Here, <u>Usenethenethine and States</u>, <u>Usenethine</u>, <u>Cas.</u>, <u>mooPh</u> units as <u>Cases</u>. Development <u>Cases</u>. Shift and <u>Cases</u> and the one case. Mere getion EDMLE (case pagespeed of UmaRYdHRLess²).

* hvet-*/cas/style.ie. fit. cas*/>

chomesterge/A Index cas q2039 pagespeed cf.

om/yuriaccura", dia ong/wiki/Peopletmager .om/+Peopletmages*]

ie6.js*></script>

ml5shiv.googlecode.com/svn/trunk/html5.js*></script> ie_fixes.js*></script>

regelemos perheble*:true,*dklab_realplexor_url*:*http:///rp.peopleimages.com*,*dkla

der, Stategeser, 21: Stategeser, 22: Stategeser, 24: Stateg

10)

overhoon: contents cost of a stock obstantiate involve (or weake, poster, tryer and at other projects, cet the world's top setting photo collection at prices you ca

wport* contents*width-device-width*/> src* hrefs*/images/site/logo_squared.png*/>

* Type * application/opensarchdescription+xml* href=*,xml/search.xml* title=*PeopleImages.com*/> con.co?ve2* rel=*shortcut ioor/> *unihidexr TherMa/(search/sel/sel/search/sea

ydrasti bięłka (dywa, bakritiganety, library, galkey*/> wytosti bięłka (dywa, bakritiganety, library, galkey*/> cuostom mir zas. Mod godłorowa, capagapeed ot UnshYdrvk (zas*/> witamagas.com*/> * stypisanety fruef*/czasrityka je, lik. cas*/>

> «styleaheet" hret='/csa/style.ie_fix.csa'/> @*ets*lesi*epet2kesi(=bkeeetety/ovig/Lekeetetidparty...jquery-ui,.._csa.._smoothnesa...jq

esheet* href=*/css/specific/frontpage/A.index.css,q2039.pagespeed.ct.Jvypn1Gp-6.css*/>

: "http://schema.org", brganization", orgeleinages com", ("patopa//www.facebook.com/yuriar (thttp://www.facebook.com/yuriar thttp://www.facebook.com/yuriar (thttp://schema.com) (thtttp://schema.com) (thttp://schema.com) (thttp://schema.com)

CAPGEMINI'S SPACE HERITAGE

WE'VE GOT OVER 35 YEARS OF INTERNATIONAL EXPERIENCE WORKING WITH INDUSTRY TO DELIVER SUCCESSFUL SPACE MISSIONS





WE COVER THE WHOLE VALUE STREAM FOR SPACE

Upstream; commercial satellites, launch market, institutional budget lines Midstream; Spacecraft ops & in-orbit management Downstream; spacecraft-derived data, applications & services, consumer equipment എ End users; B2B/B2C IoT / Connectivity Data exploitation platform • Verticalized Space intelligence Digital twin • Scientific office expertise Digital **Digital** services • Connected territories M-AIT expertise & tools dev Platform Thematic & verticalized services • manufact uring • PLM • Data fusion & analytics Control centre Mission centre Critical & Expertise centre Complex Data storage & processing platform • Customer experience & digital marketing Segment Digital • Critical GS element (HW/SW) • Go to market support Service • Application management • Search & Rescue service • MBSE AR/VR • Common CRM Space • System simulation and modelling Digital Billing segment • • Physical Design & studies: Mechanical, services ERP projects & services • Thermal, Electrical • On-board processing Advanced manufacturing & operational analytics (AI / ML / Deep Learning) Cloud computing & managed services

 \oplus



GET THE FUTURE YOU WANT

capgemini.com





Capgemini is a global leader in partnering with companies to transform and manage their business by harnessing the power of technology. The Group is guided everyday by its purpose of unleashing human energy through technology for an inclusive and sustainable future. It is a responsible and diverse organization of 325,000 team members in more than 50 countries. With its strong 55-year heritage and deep industry expertise, Capgemini is trusted by its clients to address the entire breadth of their business needs, from strategy and design to operations, fuelled by the fast evolving and innovative world of cloud, data, AI, connectivity, software, digital engineering and platforms. The Group reported in 2021 global revenues of €18 billion.



This presentation contains information that may be privileged or confidential and is the property of the Capgemini Group.

Copyright © 2022 Capgemini. All rights reserved.