

Science of Sensor System Software (S4)

EPSRC Programme Grant: Final Report

<https://www.dcs.gla.ac.uk/research/S4/>

Investigators

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This is the fifth and final report for S4. We aim not to repeat information in previous reports but focus on our overall scientific achievements and conclusions. See earlier reports for e.g. advocacy and industrial and international relationships.

1 Summary of results

The programme was inherently holistic and integrated across all four universities. Research was organised around five themes.

Autonomy. We considered a system's ability to make decisions with varying degrees of independence from human control. This included agent modelling, reasoning, human-autonomy teaming, system validation and certification, across many applications, e.g. autonomous robotics.

Spatial Modelling. We developed new representations and logics and how to evaluate and compare different topologies, with applications in Wi-Fi and LoRaWAN networks. We extended bigraphs to conditional and probabilistic rewriting, including toolsets, with applications in BDI agents. Foundational work included logics for neighbourhood spaces, bisimulations for closure spaces, sensor data interpolation algorithms, use of Matérn cluster processes that allowed us to articulate exactly the impact of non-orthogonality in LoRaWAN, and new target counting results for topologies with overlapping sensing.

Coordination. We made advances in protocol modelling, analysis, and verification, as well as network security and reliability, with applications in IoT, energy harvesting systems, and low power networks such as LoRa.

Cyber-Physical Interaction. We focussed mainly on energy, from energy harvesting to energy and battery modelling and verification, but also we studied the effects of physical environment (temperature) on sensors, with applications in IoT, LoRaWAN, and robotics. We investigated the co-design of a cyber (sensor network) and physical (water network) model to demonstrate how they impact each-other and demonstrated that both could be co-optimised accordingly.

Data Interpretation. We developed new techniques for inference and for systems re-engineering based on models inferred from interaction traces, with applications in healthcare, sensed human activities, and human system interactions. We made several advances in machine learning applied to event detection and sensor error determination, and used spatial and topological information to correct for errors and under-sampling.

Overall, the programme was highly successful, building a community of researchers who worked together as a *team* to tackle the breadth of research challenges in sensor-rich systems. A key outcome from S4 was our development of the concept of *frames of reference* [0]. Each frame articulates a different perspective and the dimensions and measurements specific to that perspective; they enable more clarity about the purpose of the system and of the model. Example frames of reference include: geographic (spatial/topological), physical, security, privacy, legal, failures and resilience, temporal, social, economic, uncertainty. We have concluded that transparency of design constraints and *verifiability by design* are key to successful modelling and reasoning – these must be considered from the outset, not post facto. For example, if the number of communication links can be bounded, why not make that bound explicit, thus making the system more verifiable.

We initiated numerous collaborations with industry including ABB, Dyson, Network Rail, NXP, Topolytics, Traak, and Thales, with varying degrees of success. On several occasions we found that after spending time learning about their system, either the research challenge did not arise from the fundamentals of sensing but from undertrained people deploying a system, or the people we were working with moved on or out of the organisation. On more than one occasion we encountered reluctance to introduce degrees of autonomy, not for safety reasons, but to protect employment. Fortunately, no one industrial case study was on a critical path.

A distinctive aspect, key to building our team ethos, was our four *research retreats* at a hotel in North Berwick. We held our final retreat in November 2022, see Figure 1. Unlike standard research workshops, where individuals talk about completed work, the goal of these 3-day events was to spend time together, working as a team, to uncover some of the deep and hard research problems that span the entire programme, to critically assess our progress so far, and to discuss and plan future research directions. North Berwick was chosen as a location that was remote-enough yet reachable by public transport. Reports from the retreat are available elsewhere and have been submitted to EPSRC.



Figure 1: Our last Research Retreat, North Berwick, November 2022.

2 Example publications

All our publications are listed in Section 7, here we provide give a small selection illustrating the breadth and depth of our research. Note the majority are authored by researchers at two or more universities in S4, or with researchers outside S4 entirely, evidence that we did work *together* within and beyond this programme.

Self-stabilising target counting in wireless sensor networks using Euler integration. Danilo Pianini, Simon Dobson, Mirki Viroli. In *Proceedings of the 11th International Conference on Self-Adaptive and Self-Organizing Systems (SASO)*. IEEE, 2017.

Making Sense of the World: Framing Models for Trustworthy Sensor-Driven Systems. Muffy Calder, Simon Dobson, Michael Fisher, Julie McCann. *Computers*, 7(4), 2018.

A Reference Architecture and Model for Sensor Data Warehousing. Simon Dobson, Matteo Golfarelli, Simone Graziani, and Stefano Rizzi. *IEEE Sensors Journal* 18. 2018.

Target Counting with Presburger Constraints and its Application in Sensor Networks. Sven Linker, Michele Sevegnani. *Proceedings of the Royal Society of London Series A: Mathematical, Physical and Engineering Sciences* 475, 2019.

Distributed Self-Monitoring Sensor Networks via Markov Switching Dynamic Linear Models. Lei Fang, Juan Ye, and Simon Dobson. In *Proceedings of the Thirteenth IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO'19)*. Umeå, SE. 2019. (Winner of runner-up best paper award.)

Discovery and Recognition of Emerging Human Activities Using a Hierarchical Mixture of Directional Statistical Models. Lei Fang, Juan Ye, Simon Dobson. *IEEE Transactions on Knowledge and Data Engineering*, 2019.

Multi-scale Verification of Distributed Synchronisation. Paul Gainer, Sven Linker, Clare Dixon, Ullrich Hustadt, Michael Fisher. *Formal Methods in Systems Design* 55(3), 2020.

Exploring the Effects of Environmental Conditions and Design Choices on IoT Systems using Formal Methods. Matt Webster, Michael Breza, Clare Dixon, Michael Fisher, Julie A. McCann. *Journal of Computational Science* 45, 2020.

Probabilistic Bigraphs. Blair Archibald, Muffy Calder, Michele Sevegnani. *Formal Aspects of Computing*, 34(2), 2022.

3 Selected Invited Talks by PIs

Calder: UK Gov expert briefing on Future Communications (OSTS 2022); Keynote at Forte Intl Conference (Italy 2022); Regius Lecture (Southampton 2022); Wilton Park meeting on AI (Foreign & Commonwealth Office 2021); Computer Science Education (Prime Minister's Council for Science and Technology 2021); Strachey lecture (Oxford 2020); Sargent Centre of Process Engineering Celebration of Systems Thinking, (Imperial College 2021); Newcastle University Computing 60th Anniversary (Newcastle 2019); BCS Karen Sparck-Jones Lecture (London 2019).

Dixon: PERSEO Summer School on Service-Based and Cloud Robotics (Majorca, 2022); IEEE UK & Ireland RAS conference for Space session] (Edinburgh, 2022); 15th Conference on Reachability Problems (Liverpool, 2021); Formal Methods for Autonomous Systems (virtual, 2021); International Symposium on Temporal Representation and Reasoning (virtual, 2020).

Dobson: Invited talk to the MAKI workshop on Autonomous decision-making in networked systems under uncertainty; Invited talk at LEISYS'2022; Keynote at the Conference on Design

and Architectures for Signal and Image Processing; invited talk (Univ. College Cork), invited talk (Univ. York); invited talk at Institute of Mathematics and its Applications (London).

Fisher: Invited talks (Lancaster, Leicester, Manchester, Sheffield universities); CPS-IoT Week Workshop on Machine Learning in Control (virtual); VORTEX Workshop (virtual); AI Summit (London), AAAI Spring Symposium "Putting AI in the Critical Loop: Assured Trust and Autonomy in Human-Machine Teams"; IET; "Assured Autonomy" workshop, Computing Research Association (Phoenix); Offshore Europe (Aberdeen); "Trust me I am Autonomous" workshop (Toulouse); ESA (Toulouse); Global Forum on AI for Humanity (Paris); NASA (San Jose).

McCann Keynotes IEEE 17TH International Conference on Distributed Computing in Sensor Systems, DCOSS 2021; and ACM International Conference on Embedded Wireless Systems and Networks, EWSN 2020; invited to do the 2022 IET/BCS Turing Talk (London and Belfast); Dagstuhl 2021; Panel member for Data-Driven Systems Engineering, Centre for Systems Engineering and innovation 10 year celebration, July 2020; and University of York Distinguished Seminar (March 2022).

4 All-hands Meetings and Formal Reports

We held the following regular all hands meetings and research retreats.

- 25-26 April 2016, Glasgow
- 14 October 2016, London
- 10 January 2017, London
- 23-24 May 2017, Glasgow
- 5 October 2017, Manchester
- 9-11 January 2018, North Berwick
- 28 February 2018, London
- 6 June 2018, St Andrews
- 8-10 January 2019, North Berwick
- 31 July 2019, Glasgow
- 8-10 January 2020, North Berwick
- 9 August 2021, online
- 8-10 November 2022, North Berwick.

This is the fourth report submitted to the EPSRC, previous reports are:

- Report 2016
- Report 2017-18
- Report 2019-2021.

5 Staffing

We are proud to have been a diverse team from 12 countries: UK, Ireland, Italy, Iran, Germany, Greece, Romania, Bulgaria, USA, China, Tunisia, Pakistan.

PDRA staff in post at the conclusion of S4

- Dr. Mengwei Xu, University of Glasgow
- Dr Mike Breza, Imperial College
- Dr Georgios Kourtis, Dr. Maryam Ghaffari Saadat, University of Manchester.

PDRA staff who have worked on S4

We have been very successful at developing our PDRAs and several have been appointed into permanent posts. In most cases, this is into a lecturing post and our research collaboration continued.

- Dr Ivana Tomic, University of Greenwich from April 2019
- Dr Oana Andrei, University of Glasgow from 2019
- Dr Michele Sevegnani, University of Glasgow from January 2020, senior lecturer from August 2022
- Dr Matt Webster, senior lecturer at Liverpool John-Moores University from July 2020
- Dr Lei Fang, lecturer at University of St Andrews from August 2020
- Dr Sven Linker, lecturer at University of Lancaster (Leipzig) from September 2020 and then KenKonzept from 2022
- Dr Fabio Papacchini, lecturer at University of Lancaster (Leipzig) from 2022
- Dr Blair Archibald, University of Glasgow from June 2022
- Dr Fatma Benkhelifa, Assistant Professor, Coventry University from January 2022
- Dr Laksh Bhatia, obtained his PhD and is now Senior Engineer, Qualcomm from November 2021
- Dr Peter Mann, lecturer at University of St Andrews from December 2022.

Our PIs have also developed.

- Michael Fisher was awarded a Royal Academy of Engineering 10-year *Chair in Emerging Technologies* in 2019.
- Simon Dobson was elected Fellow of the Royal Society of Edinburgh in 2020, and was Head of School 2017–2021.
- Julie McCann was appointed Vice Dean for Research in Imperial Faculty of Engineering, 2021-present.
- Muffy Calder was made a DBE in 2020 and was appointed to the Prime Minister's Council for Science and Technology.
- Clare Dixon and Michael Fisher were appointed Professors at University of Manchester in 2020.
- Clare Dixon was appointed Deputy Head of Research (responsible for Computer Science) in the University of Manchester's School of Engineering from 2021.

6 Future research directions

As stated earlier, a key conceptual outcome from S4 is our *frames of reference*. Most of our results in S4 address a specific perspective, or a combination thereof, and include both new techniques and their application. This is the firm foundation from which we will develop our future research: how to address the *balancing* of competing perspectives, especially for systems that require degrees of autonomy, security, reliability, transparency/verifiability, safety, and resilience.

Sustainability has gained importance over the lifetime of S4, and so we propose an additional perspective: longevity and end of life decommissioning. Techniques for this new perspective will be further developed and incorporated into an approach to balancing – to ensure that the new systems we design and deploy contribute to tackling environmental sustainability, and do not become part of the problem.

7 Publications

Submitted

Peter Mann, Simon Dobson. Towards a Framework for Assessing Sensor Placement and Error. Submitted for publication, 2022.

Blair Archibald, Muffy Calder, Michele Sevegnani. Practical Modelling with Bigraphs. Submitted for publication, 2022.

Peter Mann and Simon Dobson. Belief Propagation on Networks with Cliques and Chordless Cycles. Submitted to Physical Review E.

2022

Blair Archibald, Muffy Calder, Michele Sevegnani, and Mengwei Xu. Modelling and Verifying BDI Agents with Bigraphs. *Science of Computer Programming* 215, 2022.

Fabio Papacchini, Claudia Nalon, Ullrich Hustadt, and Clare Dixon. Local is Best: Efficient Reductions to Modal Logic K. *Journal of Automated Reasoning*, 2022.

Blair Archibald, Muffy Calder, Michele Sevegnani. Probabilistic Bigraphs. *Formal Aspects of Computing* 34(2), 2022.

Georgios Kourtis, Clare Dixon, Michael Fisher, Alexei Lisitsa. Parameterized Verification of Leader/Follower Systems via First-Order TL. *Formal Methods in System Design* 58(3):440–468, 2022.

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Blair Archibald, Kyle Burns, Ciaran McCreesh, Michele Sevegnani. Practical Bigraphs via Subgraph Isomorphism. In *Proc. 27th International Conference on Principles and Practice of Constraint Programming (CP)*, 2021.

Blair Archibald, Muffy Calder, Michele Sevegnani, and Mengwei Xu. Probabilistic BDI Agents: Actions, Plans, and Intentions. In *Proc. SEMF*. LNCS, 2021.

Blair Archibald, Géza Kulcsár, Michele Sevegnani. A Tale of Two Graph Models: A Case Study in Wireless Sensor Networks. *Formal Aspects of Computing*, 2021.

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