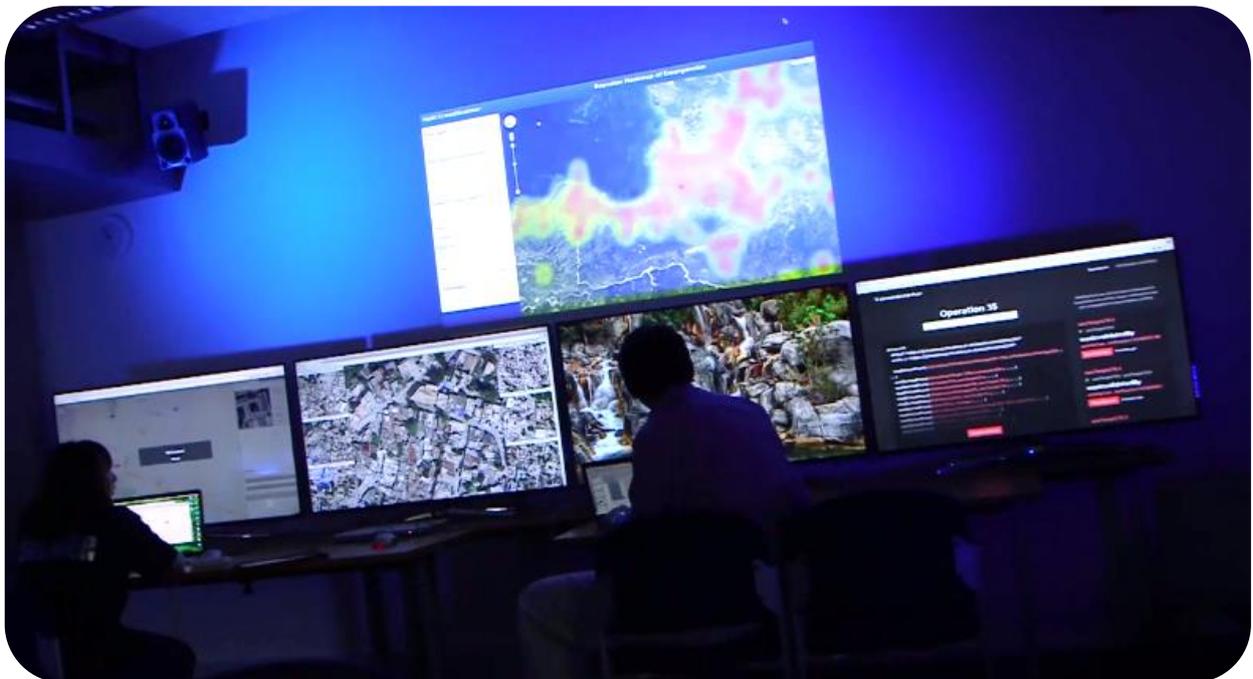


ORCHID

The Science of Human-Agent Collectives



FINAL REPORT
www.orchid.ac.uk

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Foreword



The ORCHID project tackled one of the key challenges in modern computer science – how humans and intelligent software systems can work together in a seamless and effective manner in challenging real-world applications. Such *human-agent collectives* are required to make sense of the volume, variety and pace of data that is available today from a myriad of sources and devices. Only by flexibly combining the best of human ingenuity and problem solving with machine intelligence can we hope to build the complex socio-technical systems required by tomorrow’s applications.

ORCHID tackled this grand challenge by undertaking world-class basic research in areas such as artificial intelligence, human-computer interaction, machine learning and ubiquitous computing. This research often involved the bringing together of these different disciplines to develop sufficiently broad-based models. There was a strong ethos of building and deploying prototypes “in the wild” to gain insights into how users interact with them. These insights were then used to generate new fundamental scientific challenges. The project’s focus was on applications in the areas of disaster response, smart energy systems and citizen science, but the impact and application of human-agent collectives goes well beyond this.

In a project of this scale, the people and the way they work together is a fundamental determinant of success. This was one of the project’s strengths. We received long-term, flexible funding that enabled us to develop critical-mass and explore a good number of exciting opportunities; a number of which only developed during the course of the project. The researchers, at all levels and all institutions, worked together, discussed ideas, developed theories and built software systems. This commonality of purpose was central to the project’s success.

Although the project has now finished, its research agenda and research network will continue to flourish. ORCHID directly trained and employed fifty researchers and PhD students and has spawned thirty follow-on projects worth £15 million. It has also established a new multi-disciplinary research community and deployed real-world applications of human-agent collectives that will endure and be further developed.

I hope you enjoy reading this report and finding out more about the exciting world of human-agent collectives.

A handwritten signature in blue ink that reads "Nick Jennings". The signature is written in a cursive, slightly slanted style.

Nick Jennings CB, FEng
Principal Investigator of ORCHID
Regius Professor of Computer Science
University of Southampton, March 2016.

Introduction

The computer has come a long way from its initial role as a scientific tool in the research lab. We live in a world where a host of computer systems, distributed throughout our physical and information environments, are increasingly implicated in our everyday actions. Computer technologies impact all aspects of our lives and our relationship with the digital has fundamentally altered as computers have moved out of the workplace and away from the desktop.

Networked computers, tablets, phones and personal devices are now commonplace, as are an increasingly diverse set of digital devices and services built into the world around us. Data and information is generated at unprecedented speeds and volumes from an increasingly diverse range of sources and via ever more sensor types. It is then combined in unforeseen ways, limited only by human imagination. People's activities and collaborations are becoming ever more dependent upon, and intertwined with, this ubiquitous information substrate.

As these trends continue apace, it is becoming apparent that many endeavours involve the symbiotic interleaving of humans and computers. Moreover, the emergence of these close-knit partnerships is inducing profound change. The ability of computer systems to sense and respond to our on-going activities in the real-world is transforming our daily lives and shaping the emergence of a new digital society for the 21st century. More specifically, rather than issuing instructions to passive machines that wait until they are asked before doing anything, we are working in tandem with highly inter-connected computational components that act autonomously and intelligently (aka *agents*). This shift is needed to cope with the volume, variety, and pace of the information and services that are now available.

It is simply infeasible to expect individuals to be aware of the panoply of potentially relevant possibilities and be able to pull them together manually. Computers need to more proactively guide users' interactions based on their preferences and constraints. In so doing, greater attention needs to be given to the balance of control between people and machines. In many situations, humans are in charge and agents predominantly act in a supporting role, providing advice and suggesting options. In other cases, however, agents are in control and humans play the supporting role (e.g., autonomous cars and algorithmic trading on stock markets). Moreover, these relationships may change during the course of an activity (e.g., a human may be interrupted by a more pressing request and so take a less hands-on approach to the current task or an agent may encounter an unexpected situation and have to ask for human assistance for a task it was planning to complete autonomously).

To fully realise this vision, a principled science that allows us to reason about the computational and human aspects of these systems is required. Starting the development of this science was the core research objective of ORCHID. With multidisciplinary expertise in the areas of artificial intelligence, machine learning, crowdsourcing, the Internet of Things and human-computer interaction, the ORCHID team has driven the science of human-agent collectives (**HACs**). It has

also shown how HACs can be engineered and applied to real-world applications in the critical domains of energy systems, disaster response and citizen science.

In more detail, HACs exhibit a close partnership based on flexible social interactions between humans and agents. As well as exhibiting increased autonomy, such systems are inherently open and social. This openness means participants need to continually and flexibly establish and manage a range of social relationships. Thus, depending on the task at hand, different constellations of people, resources, and information need to come together, operate in a coordinated fashion, and then disband. The openness and presence of many distinct stakeholders, each with their own resources and objectives, means participation is motivated by a broad range of incentives – extrinsic (e.g., money or tax-benefit), social or image motivation (e.g., public accreditation or leaderboard position) or intrinsic (e.g., personal interest in a social cause) – rather than diktat.

HAC systems exhibit a number of distinctive features that make them particularly challenging to engineer, control and predict. Their open nature means control and information is widely dispersed among a large number of people and agents with different aims and objectives. The various system elements exhibit a range of availabilities, some are persistent others are transient. The independent actors within a HAC need to coordinate flexibly with people and agents that are themselves adapting their behaviour and actions to the prevailing circumstances to best achieve their goals. The real-world context means uncertainty, ambiguity and bias are endemic and so the agents need to handle information of varying quality, trustworthiness and provenance. Thus, techniques are required to provide an auditable information trail from the point of capture (a sensor or a human participant), through the fusion and decision processes, to the point of action. Moreover, the agents have to reason about the trust and reputation of their collaborators to take the best course of action. Finally, in many cases, it is important that the collective action of the volitionally participating actors results in desirable social outcomes (such as fairness, efficiency or stability). These features of HACs require us to:

- understand how to provide *flexible autonomy* that allows agents to sometimes take actions in a completely autonomous way without reference to humans, while at other times being guided by much closer human involvement.
- discover the means by which groups of agents and humans can exhibit *agile teaming* and come together on an ad hoc basis to achieve joint goals and then disband once the cooperative action has been successful.
- elaborate the principles of *incentive engineering* in which rewards are designed so that participants are encouraged to take actions that generate socially desirable outcomes.
- design an *accountable information infrastructure* that allows the veracity and accuracy of seamlessly-blended human and agent decisions, sensor data and crowd-generated content to be confirmed and audited.

Research Achievements

The project team involved a number of leading University groups: the University of Nottingham (Tom Rodden), the University of Oxford (Steve Roberts and Michael Osborne), and the University of Southampton (Nick Jennings, Luc Moreau, Alex Rogers and Gopal Ramchurn). During its lifetime, ORCHID employed 50

Research Fellows and PhD students. It had the following organisations as industrial collaborators: BAE Systems, Secure Meters Ltd., the Australian Centre for Field Robotics (ACFR) and Rescue Global. It also employed a Knowledge Transfer Officer, David Nicholson, who was jointly funded by EPSRC and BAE Systems, and a project administrator (Angela Westley). The project received advice from an Independent Scientific Panel, whose members were Brian Collins



(University College London), Yolanda Gil (University Southern California), Thore Graepel (Google Deepmind), David Parkes (Harvard University) and Alan Winfield (University of West of England) and an Industrial Advisory Group whose members were Antony Waldock (BMT), Henry Tse and Robert Johnston (BAE), Kaushik Ghosh (Secure), Salah Sukkarieh (ACFR) and David Jones (Rescue Global).

The research within ORCHID was split into five inter-related work areas (WAs), each of which is described in more detail in the remainder of this section.



The project produced 250 publications, including 60 in journals, that have attracted over 4,500 citations. Of these, 35 were between more than one project partner, 11 involved an industrial co-author, 95 involved an international co-author and 8 were either shortlisted for, or won, a best paper award. The project web-site is a key resource and attracted over 20,000 users and 70,000 page views since its inception. See Appendix B for a full report of ORCHID's key performance indicators.

In addition to those listed in this section, a number of research achievements relate to knowledge transfer activities, including the award of six patents and participation in Angel Thunder, one of the world's largest search and rescue exercises. Moreover, there have been 30 follow on grants worth over £15 million. These are detailed in the section on Research Impact.

Flexible Autonomy

What was the challenge?

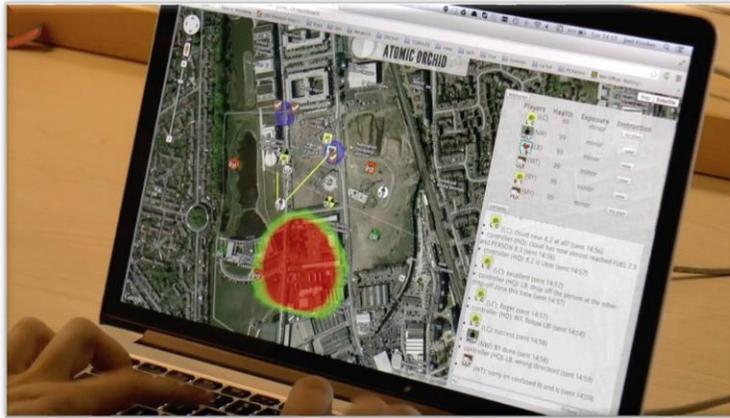
This Work Area (WA1) was led by Tom Rodden and its initial objectives were:

We will focus on the establishment of the key interactional principles between human and software agents that are needed to allow a sense of flexible autonomy to be established, monitored and amended in a context sensitive manner. These principles will be built into key mechanisms and reflected in the ways we represent and reason about these systems. Key objectives in establishing these principles are as follows. (i) The **development of new presentation and interaction techniques** to allow users to understand the actions of large collections of independent systems as they reason and act on behalf of users. (ii) The **development of new control models and representations** that allow dynamic and fluid interactive arrangements of agents and users. For example, allowing authority relationship between users and agents to change in different contexts and agents to work under varying levels of supervision. (iii) The **development of techniques to recognise human activity** to allow agents to reason about human interaction so they might exploit this understanding to augment and support the actions of users. (iv) An **elaboration of the effectiveness of different styles of interaction** and their role in HACs. For example, when should users give direct orders that agents must obey? When might users express their broad desire and allow these to be re-interpreted by agents? Under what circumstances should agents instruct users what to do and when should users be able to question them?

What did we achieve?

Our work on the **development of new presentation techniques** focused on research ‘in the wild’. This involved the development, deployment and assessment of HACs that addressed energy and sustainability, disaster response and citizen science. Each of these were characterised by research outputs in the leading HCI and AI venues and the deployment and release of software systems. Highlights included:

- The development and deployment of AgentSwitch, an agent-based system that analysed people’s energy use profiles in order to recommend a switch to the most appropriate energy tariff. The technical details of the work were published at a range of AI and HCI conferences. The work exploring the role of agents in energy monitoring in the home was published as a best paper at CHI and was subsequently invited to be presented at IJCAI. This work was complemented by a range of energy-based HAC deployments looking at more specialist roles of agents, including managing battery use, leading to a broad range of publications at CHI.
- The development and deployment of a physical HAC infrastructure within the disaster response domain, called AtomicORCHID, which allowed a range of real-world users to take part in a physical role-based experience around responding to a radiation leak. This used a game-based approach to allow a number of players to undertake exercises based around recovery of resources. AtomicORCHID played a key part in the HAC-ER demo, which won a best paper award at AAMAS 2015. The public release of the software and system has been managed through a dedicated website (<http://hacplanning.com/>).



The work on AtomicORCHID was complemented by an exploration of user interaction with agent controlled UAVs. This work on multi-UAV control was published at IJCAI 2015 with a follow-up grant proposal currently being written to further explore the use of functional near-infrared spectroscopy (fNIRS) to support the user control of multiple UAVs. Our exploration of AtomicORCHID

was enhanced by a close partnership with Rescue Global, a charity offering first response support. A series of initial ethnographic studies of large-scale exercises allowed us to understand working practices involved in disaster response. These led to publications in leading ACM conferences including CSCW and CHI. As a result of these investigations we developed an augmented bird-table, to support cooperative interaction of disaster responders, which was subsequently trialled in a real-world setting and which forms the core of a follow-on project with Rescue Global focused on exploiting this work.

- The development, deployment and study of a series of biodiversity applications exploiting mobile devices as a means of gathering information donated by citizens. The most notable example of this was a deployment and study of a mobile app to detect the New Forest cicada. This work was published at CHI, where we outlined a range of key principles for the design of interactive applications for biodiversity.

Our user-centred approach to research also allowed us to work with users to understand the implications of foundational principles. This included work on key interactive principles and work on understanding provenance. For example:

- Exploring the ways in which users might interact with and orientate to provenance. To explore this we developed an on-line interactive provenance game that recruited several hundred users leading to a substantial provenance set. The work was published as a paper at the ACM CHI conference as one of the first examples of a real-world use of the PROV standard.
- Work on **interactive dialog with agents** that focused on the language used in receiving instruction. Our particular emphasis was on the type of language used by an agent to instruct a user. These trials involved close cooperation with corpus linguists to understand the nature of the language used, focusing specifically on the role of vague language. The resulting work was published in the ACM Human Agent Interaction conference series.
- Work on the effectiveness of different styles of interaction explored the development of a HAC pattern language. The patterns will be consolidated in a publication in 2016. A version of the patterns have already been developed into a set of mixed reality game pattern cards and are now being extended for wider distribution as part of the Nottingham Impact Accelerator Account.



- **Capturing and representing human activity** in response to growing societal concerns about the role of agents and data privacy. We focused particularly on the issues of ethics and consent associated with these form of systems and the design challenges involved. We undertook a series of expert interviews and developed material suitable for presentation in policy forums. In addition to publishing this work at CHI, we developed a series of ideation cards, which focus on embedding legal and ethical considerations in the design of intelligent agent-based systems. This work was published at CHI 2015 and has matured to be the core of a joint UK-US project, Design by Privacy, involving Microsoft, McAfee and Intel. The cards were made freely available via <http://www.designingforprivacy.co.uk/> and were subsequently used by the BBC.

What are the remaining challenges?

Our work represents the starting point for a broad set of issues as HACs continue to mature. Key open research challenges in this area include:

- The need to balance the power of the use of HACs with **support for consent and withdrawal** for HACs, particularly when agents are embedded in a “smart” environment such as those envisaged by the Internet of Things.
- As HACs mature and become more prevalent, they will raise fundamental issues on the implications and effect of **blended human and machine intelligence**, which will require us to revisit our current understanding of both artificial and human intelligence.
- Agents will need to become more accountable as they increasingly act on behalf of human participants or instruct users. Techniques will be needed to allow agents to **provide an open and transparent account** of their rationale. How this is captured and presented to users is an open question in the development of HACs.

Agile Teaming

What was the challenge?

This Work Area (WA2) was led by Alex Rogers and its initial objectives were:

We will focus on the development of key mechanisms and formalisms to deliver the agile teaming described above and how these are made available to users. Key objectives in establishing these mechanisms and formalisms include the following. (i) The **development of new metaphors and design guidelines** that enable effective teams to be formed by interleaving humans and agents such that they can work collectively toward a particular task, while fully exploiting the specific advantages and constraints of both parties. (ii) The **development of mechanisms and algorithms** that allow humans and agents within a group to effectively coordinate their activities and actions to collectively maximise their utility. (iii) The **integration and demonstration** of these approaches within exemplar applications within the domains of energy systems and disaster response.

What did we achieve?

In terms of the **development of new metaphors and design guidelines**, the project provided and published a set of design patterns for human-agent collectives. These design patterns were informed by the range of demonstration systems deployed throughout the project including AtomicORCHID, TariffAgent, the New Forest Cicada Project deployments of the Cicada app, and engagements with Rescue Global including shadowing of their operations at Disaster City (the world's largest search-and-rescue training facility) and Angel Thunder (an inter-agency, international training exercise). The design patterns were developed through a sequence of workshops involving researchers across the ORCHID academic partners and representatives from Rescue Global.

In terms of the **development of mechanisms and algorithms** that allow humans and agents within a group to effectively coordinate their activities, work has addressed two algorithmic frameworks. The first considers the use of coalition formation, building on the existing game theory literature, to develop computationally efficient approaches to: (i) calculate the near optimal sub-groups of agents (be they human or software entities) to form to perform tasks, and (ii) to calculate the fair allocation of any reward earned by the sub-group by the efficient calculation of Shapley value, exploiting both approximation schemes that provide bounds and features of the coalition characteristic function, in the context of coordinating cooling and heating loads across coalitions of buildings. This work has culminated in the publication of a wide-ranging review article in Artificial Intelligence Journal describing both the existing state of the art and ORCHID's contributions in this space. The second algorithmic framework has considered approaches to allow an existing sub-group of agents to coordinate tasks. In the area of rescue robotics, this work has developed computationally efficient algorithms to divide search and rescue tasks between UAVs of different capabilities while explicitly representing uncertainty over the type and location of future tasks, has developed Bayesian approaches to simultaneously infer both the trustworthiness of a human volunteer, and the outcome of a crowdsourced human computation task such as image or text classification, and



has developed algorithms and software systems to allow multiple crowdsourced human volunteers to contribute to the control and sensing tasks of UAVs in real-time.

In terms of the **integration and demonstration of these approaches**, the project has developed and demonstrated many of these solutions in deployed systems. The design patterns for human-agent collectives builds strongly on the deployment of the AtomicORCHID platform as a mixed reality game, and TariffAgent as an experimental energy purchase system, that allowed ORCHID researchers to explore human-agent interaction in the real-world. Many of the above technologies, particularly those addressing UAV control, and the use of Bayesian inference of crowdsourced data, were also deployed in the final integrated disaster management demonstrator HAC-ER. Similarly, the work on crowdsourced UAV image analysis has been deployed and demonstrated within a live online system, where human volunteers performed image labelling from live UAV video feeds in a disaster response setting.



Much of the work is also being taken forward in related projects. The agile teaming approaches demonstrated within AtomicORCHID are being further developed in collaboration with Rescue Global as part of an augmented bird-table system, which will form part of Rescue Global’s ongoing disaster management operations. Similarly, the coalition formation and coordination approaches developed and demonstrated in simulation in the context of coordinating cooling loads in coalitions of buildings, is being further developed within an Innovate UK funded project (Adaptive Demand Response) with KiwiPower (the UK’s leading aggregate demand response company).

What are the remaining challenges?

The key open research challenges in this area are:

- **Scaling to millions of agents:** While work within the ORCHID project has led to coalition formation and coordination being applied to systems of tens to hundreds of agents, it has yet to be demonstrated at huge scale, perhaps involving millions of agents. This presents both algorithmic challenges since at this scale, only extremely low computational complexity algorithms can be used, and also deployment challenges in building decentralised systems to perform the necessary computation at scale.
- **Eliciting agent preferences:** Work within ORCHID has developed computationally efficient approaches to calculating near-optimal allocations of agents to coalitions, but these assume that the preferences and utilities of all agents (software and human) are known *a priori*. In many cases, this requires significant prior collection of information, and as an alternative it may be preferable to propose solutions and then use the agents’ responses to those proposed coalitions as a form of preference elicitation, learning the utilities as the allocation is calculated. Algorithms that work in this manner have not been described in the literature.
- **More real-world deployments:** While work within the ORCHID project has demonstrated the use of human-agent collectives in a number of real-world settings further work is needed to both broaden the range of applications considered, as well as explore collaboration possibilities, in situations of greater variety in scale, pace and extent.

Incentive Engineering

What was the challenge?

This Work Area (WA3) was led by Steve Roberts and its initial objectives were:

We will focus on the development of mechanisms and methods of approach that provide a means of influencing the behaviour of individual actors (humans and software agents) and groups, where there is no direct means of controlling the internal workings of the participants. In particular, the key initial objectives for this work are as follows. (i) Evaluate a **principled value for information, action and strategy** to inform an agent's assignment of utility. (ii) Develop methods to **incentivise humans and agents to gather and utilize information and act** in uncertain, dynamic environments. (iii) Develop **methods by which communities and social networks and coalitions of humans and agents** can be analysed, tracked and forecasted. (iv) Determine **how and what (weak or indirect) control** needs be exerted over collectives of humans and agents to achieve global objectives by engaging in joint actions.

What did we achieve?

We regard Incentive Engineering as designing systems in which agents' rewards are designed in such a way that the actions that are encouraged generate socially desirable outcomes. Although there is much work in psychology on the use of *nudges* and the like, we explicitly avoid such subliminal social engineering and aim to induce incentives through the provision of *value* to the agents.

In more detail, in terms of developing a **principled value for information, action and strategy** we have refined, developed and understood the relationships between intelligent task assignment, uncertainty and preference learning. We aimed to modify such algorithms to accommodate humans within the loop more naturally and thus, mitigate the need for costly incentives and reduce disincentives.

Further we developed the theoretical underpinning of how **humans and agents can be incentivised to gather and utilize information**. We considered incentives for humans to operate within a HAC as not only direct incentives (money, knowledge, etc.), but also engineering software agents to act in a way that encourages humans to engage with them.



We explored the intimate relationships and **methods that exist between dynamic social networks and coalitions of agents and humans**. Investigations into the use of group-level, rather than individual-level, incentives and weak control were explored, along with further integration of provenance and inferred trust. We drove forward the application domains as foundations for testing and **comparing incentive mechanisms and weak control**. This was achieved by evaluating the effect of (ethical) weak control on human agents and more extensive empirical testing via experiments on HACs

using our network of demonstrators in Citizen-science (Zooniverse, Cicada app) and crowd-generated information (CollabMap, AtomicORCHID) both in the lab and for real world situations (for example, in response to the Nepalese earthquake in April 2015).

In terms of developing a **principled value for information, action and strategy** we have continued the development and exploitation of dynamic methodologies for tracking user policies and value of information in large, real-world citizen science, crowdsourcing, energy and disaster response environments. In particular we have:

- Developed a system for intelligent tasking, using a joint utility function of information value (system performance) based upon the selection of tasks and users so as to maximise overall utility and minimise the cost of incentives.
- Developed DynIBCC, which can track the effect of incentives on accuracy, and used this to determine the types of tasks that affect an individual's reliability. This is incorporated into our intelligent tasking framework, to select tasks that collect the most information by balancing current information needs with incentives.
- Developed approaches to infer a human's utility function from observing preferred actions instead of constant direct questioning.

For the work on **how humans and agents can be incentivised to gather and utilize information** we have developed our theory and practice around these major topics:

- Financial incentives have been explored in mixed software and crowdsourced systems; for example, in the TREC challenge work, individual workers were paid a fee for their assessment of documents based on how long the task was expected to take.
- BudgetFix used a multi-armed bandit approach to decide on the best worker in crowdsourcing applications. This efficiently balances budget allocation between find, fix or verify a task. It gives theoretical performance guarantees and significantly outperforms rival approaches.
- The use of beneficial information as an incentive. For example, work on thermal modelling and forecasting (as part of AgentSwitch and MyJoulo) has enabled users to see the benefits of changing thermostat settings.
- The development of a suite of algorithms which inform rescue services of efficient urban evacuation strategies. This incentivises the rescue services to act as the risk envelope is known.
- The New Forest Cicada work developed user engagement incentives via knowledge dissemination such as public science events and minimised disincentives by incorporating best-practice design into a smartphone app and coordination of events.
- The use of empirical research on referral incentives in crowdsourcing was applied to fund-raising for Cancer Research UK. This study concluded that high levels of rewards correlate with high sharing behaviour, but correlations with low/multi levels of rewards are inconclusive.
- The use of reverse incentive engineering for task allocation to volunteer first responders in AtomicORCHID. Here, the aim was to disincentivise task rejection by showing critical deadlines to users that were predicted from sensor readings.
- The development of mechanism design approaches for ridesharing schemes aimed at incentivising agents to reveal their true valuation even when their information is uncertain. This method is applicable to dual-role exchange markets where people can be both buyers and sellers in trading goods.

For the **relationships and methods that exist between dynamic social networks and coalitions of agents and humans** we have developed the following:

- Integrated probabilistic community discovery with Bayesian classifier combination to aggregate citizen scientists into communities based on the similarity of decision-making policies (e.g., community-based crowdsourcing). This was applied to a Zooniverse data set that enabled us to track community evolution as citizen scientists classify new objects.
- In work on provenance graphs from the CollabMap application, we have shown that perceived trust in information can be inferred from the graph.
- From the AtomicORCHID provenance networks we designed an algorithm to extract meaningful summaries of events to help participants as they consider accepting or rejecting the Planning Agent's suggestions.

To drive forward the application domains as foundations for testing and **comparing incentive mechanisms and weak control**, we have:

- Developed a set of compelling, realistic test platforms, such as AtomicORCHID, the Cicada app, the augmented bird-table (for use in disaster response management) and others mentioned above.
- Undertaken field trials of energy management systems (TariffAgent) where users work in collaboration with an agent to choose the cheapest tariff. Investigation has also been undertaken into interaction design to help users minimise their cost.
- Furthered the integration of ORCHID methodologies into the Zooniverse Citizen Science environment and produced results indicating the approaches taken are transferable with ease between data sets.
- Applied ORCHID crowdsourcing technology to a real world disaster response situation with Rescue Global immediately following the April earthquake in Nepal in 2015. This was achieved by use of the Zooniverse platform.

What are the main open challenges?

The key open research challenges in this area are:

- The use of *nudges* and other known psychological effects to enable weak coercion of human agents. There is a wealth of information highlighting the fact that human responses can be manipulated by re-presentation of material in different formats. Integrating this with the more transparent mechanisms of incentives in the ORCHID project is a major challenge, both technically and ethically.
- Developing a collaborative game-theoretic approach to human-agent collectives. Although we have achieved much in the ORCHID project, formalising the HAC methods in terms of *human-machine game theory of mind* is still an open research topic.
- Adaptation and dynamics in our ORCHID models are achieved by tracking the behaviours of agents, be they human or software. Being able to forecast and make current decisions and actions on the basis of long-term utility is a well-proven method for control, but has had little impact in systems involving human beings, due to the apparent complexity of behaviour. Some work in ORCHID has touched upon this research, but much more lies open.

Accountable Information Infrastructure

What was the challenge?

This Work Area (WA4) was led by Luc Moreau and its initial objectives were:

We will focus on the establishment of the key principles underpinning an accountable information infrastructure, and on the design of its architectural foundations. Whereas provenance tends to be detailed, providing an explicit account of how information was derived, trust and reputation tend to be measures of the quality of such information. Given this, several approaches have been proposed to derive the latter from the former. However, their varied nature in terms of representation and size imply different techniques to gather, manage, reason over and query them. In particular, ORCHID aims to integrate them in a coherent manner in the accountable information infrastructure. To this end, key objectives include the following. (i) The **specification of the information infrastructure underpinning HACs**, including common data models, representations and APIs to share and access accountable information uniformly. (ii) The definition of **models for provenance/trust/reputation** of information and their source in HACs. Models and algorithms will also be designed to support crowd generated content, uncertain information, incomplete and conflicting provenance, and anonymity and pseudonymity for privacy concerns. (iii) The **design of accountability services**, for online and offline use, based on a decentralised, large-scale architecture for capturing and reasoning over provenance/trust/reputation. These will exploit existing cloud infrastructures. (iv) The development of **techniques to manage provenance/trust/reputation over variable timescales** with an emphasis on the computational and ethical issues that may emerge from long lived information.

What did we achieve?

We devised a model of provenance for Human-Agent Collectives centered on three concepts: *entities* are data sets, decisions, votes, plans, or documents; *activities* may be approving, planning, or writing; *provenance agents* can be organizations, humans, software agents, services, or collectives. A further set of associations relates those concepts. The model was applied to a wide range of HAC applications.

The development of the provenance model did not happen in isolation in the confines of the ORCHID project. Instead, it was developed through a standardisation activity that we led. This took place under the auspice of the World Wide Web Consortium (W3C), the standardisation body for the Web, by means of the Provenance Working group, whose charter was to define provenance for the Web. ORCHID was able to influence PROV, the W3C standard for provenance; validate PROV by implementing it in several HACs; and therefore establish its interoperability. This standardisation activity allowed ORCHID to have impact well beyond its immediate collaborators and applications.

Having defined the model for HAC provenance, we adopted it in several HAC applications and delivered original provenance-based functionality. In its most basic usage, provenance can be used to audit applications, allowing the details of past executions to be provided. In CollabMap (see HAC Applications section), we used provenance as a mechanism to determine the quality of crowdsourced artifacts and the reliability of crowd workers. In the HAC-ER ORCHID demonstrator, provenance was used to determine dependencies between decisions in distributed systems. As a result, notifications were pushed to relevant parties when knowledge was being invalidated with a view to trigger re-planning.

A reference implementation of the accountable information infrastructure was built in the form of a provenance store, offering user interfaces but also REST APIs for humans and agents to

store, access, and manipulate provenance information. This software infrastructure is available from <http://provenance.ecs.soton.ac.uk>, and is accompanied by tutorials, blogs, and data sets.



ORCHID laid the foundations for provenance analytics, with methods to derive trust from provenance, graph-metrics based predictive models to rate artifacts, and a summarisation technique to identify

common patterns and outliers. ORCHID also investigated how humans can interact with provenance. With the “*Apocalypse of the Ministry of Provenance*”, an online alternate reality game, ORCHID engaged over 300 players, manipulating thousands of provenance graphs in a 1984-like plot. Interviews conducted at the end of game confirmed the provenance model was intuitive to understand, revealed some concerns regarding privacy, and suggested useful graph layouts for presenting provenance.

What are the remaining challenges?

The key open research challenges in this area are:

- **Provenance management.** Having deployed provenance in multiple HACs, we observed that the human effort and expertise required may hamper widespread adoption of provenance. The analogy is early Web servers, for which publishers had to craft html resources by hand, manage files, and configure services themselves. Those days are long gone: style sheets, frameworks, content management systems are now routine in the Web world. A similar approach is required for provenance management, combined with methodological guidelines to help developers and non-experts to become provenance conscious and creators.
- **Accountability versus ethics.** Provenance is a foundational layer to accountability, by its ability to describe how humans, agents, and collectives in general, may have influenced some data. Provenance, however, logs people’s actions, and provenance analytics, may be able to make inferences about them. Therefore, *consent* is a crucial step to allow this to happen, and privacy-by-design should also be applied to provenance and associated inferences. There are still open questions in this context: how can the trade-off between accountability and privacy be managed? How should access control be enforced on provenance and associated data? What is the overall ethical governance framework for such systems? How can meaningful and customisable consent be supported?
- **Streamed provenance analytics.** ORCHID has made great strides in developing analytics techniques over provenance. However, ever more HACs are designed to operate 24/7, which means that analytics can no longer run after completion of programs. Instead, the ability to continuously process provenance requires a stream-oriented approach, in which analytics algorithms are conceived to process provenance incrementally.

HAC Applications

What was the challenge?

This Work Area (WA5) was led by Gopal Ramchurn and its initial objectives were:

The specific objectives are as follows. (i) **Define vignettes that generate use-cases for HAC systems** that reflect the level of maturity of the developed HAC technologies. Through outreach exercises (workshops, symposia, and other domain-specific forums) and our various advisory groups, the vignettes will be enriched and enhanced. This may include looking outside the initial exemplar domains of energy systems and disaster response as new opportunities present themselves. (ii) Develop a **methodology for the construction of HAC systems** that can be used by researchers and practitioners that combines all the constituent components into a coherent overarching framework. (iii) Design applications that both **collect domain data** from deployments and **simulate challenging domain-specific problems** with high fidelity. Initially, user applications with rapid up-time will be developed that permit the collection of sizeable datasets with regards to user behaviour and system performance and, in the long term, act as vehicles for evaluating ORCHID technologies 'in the wild'. In addition, simulations will be designed to contain an extensive set of use-cases, coupled with a benchmarking framework. (iv) As technologies mature from other work areas, they will be **evaluated in both real-world settings (through user trials) and simulation platforms**, feeding back new datasets and requirements. (v) Construct demonstrators to **showcase HACs to domain experts** and to **obtain feedback** from the public, academics and policy makers that will help identify new requirements and highlight the associated ethical issues.

What did we achieve?

ORCHID focused on three core application areas, namely (i) disaster response, (ii) smart energy systems and (iii) citizen science. For each of these application areas, we developed a number of vignettes inspired by real-world events and contexts. For example, in the disaster response domain, our work was inspired by the emergency response efforts during the Haiti earthquake and the Fukushima disaster. In the smart energy systems domain, we considered a range of challenges brought about by the deeper penetration of intermittent renewable energy technologies and the need for homes to be more responsive to varying supply. In terms of the citizen science domain, we studied existing deployments such as Zooniverse but also evolved our own platforms (see more details below) in an attempt to address key societal and ecological challenges.

Methodological Contributions

The evaluation of HAC technologies "in the wild" posed a significant challenge as such technologies are still very much in their infancy and it was important to immerse users in futuristic scenarios where such HACs would be commonplace. Given this, we proposed a number of approaches to the evaluation of future technology. For example, in the smart energy systems domain, we use "storyboarding the future" with the juxtaposition of contrasting scenarios that talk about the use of HACs in the home to control the use of appliances and to choose real-time energy tariffs. In the disaster response domain, we showed how it was important to iteratively build initial prototypes for situational awareness and test them with both experts and non-expert users to draw out key interactional and algorithmic issues that arise when building HACs for real-time emergency response applications. Both strands of work led to award-winning papers at CHI and AAMAS respectively.

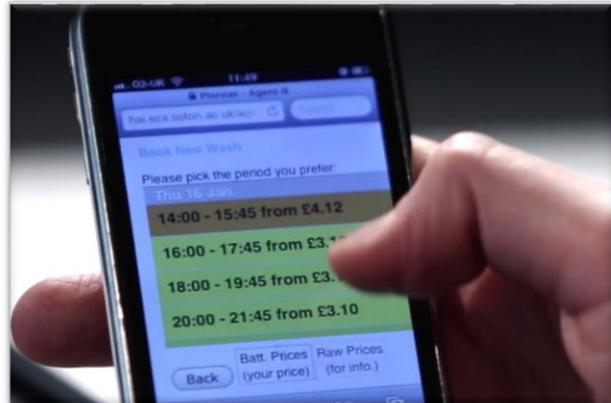
HACs in Action

Over the lifetime of the project, we built a number of applications that incrementally explored the range of scientific challenges that need to be addressed to develop effective HACs in a range of diverse domains (see Appendix A for full details). Specifically, we developed the following systems that were, on aggregate, evaluated with over 50,000 users and directly informed the working practices of organisations such as Hampshire County Council, Department for Energy and Climate Change (DECC), Rescue Global, The New Forest Commission and British Gas:

- AgentSwitch (agentswitch.com): a cloud-based app that collects smart meter data and predicts future energy consumption in order to provide advice on the choice of energy tariffs. AgentSwitch is currently being bootstrapped for commercialisation. Some of its components are currently being exploited by the Centre for Sustainable Energy to help energy advisors.
- AtomicORCHID (hacplanning.org): a mixed-reality game inspired by real-world teaming challenges faced in emergency response. The platform has been opened to use by the research community to try out different planning algorithms and interactional arrangements of emergency response commanders and planning agents.
- Augmented Bird-table: an interactive system that uses computer vision and projections and can be used with any physical map. It has the potential to empower organisations, decision makers and responders with the tools and information they need, in a timely manner, to more effectively and efficiently save lives and respond to disasters.
- HAC-ER: a prototype disaster response system based on Human-Agent Collectives. The system comprises a multi-UAV coordination system, a crowdsourcing component to gather information from inhabitants of an affected area and create heatmaps of the disaster zone, the AtomicORCHID coordination component, and a provenance tracking tool. HAC-ER is a complete HAC demonstrator that shows how humans and (physical) agents can be interleaved in flexible and agile teams.
- TariffAgent: a prototype smart grid system tested in trials with 20 households, has been developed to explore issues of how users might live with differential energy tariffs.
- The Cicada app (newforestcicada.org): a smart phone app to help locate the New Forest cicada – this has been downloaded by over 5,000 members of the public.
- CollabMap (collabmap.org): a crowdsourcing system to construct emergency maps in the aftermath of major disasters. CollabMap generated maps that permitted the high-resolution simulation of evacuation around the Fawley oil refinery (near Southampton). CollabMap was deployed with over 100 local users and generated over 30,000 annotations.



- The MyJoulo home heating advice system was deployed (over 2,000 users to date) as part of a DECC study into the requirements of smart heating controls, and won the British Gas Connected Homes start-up competition. During 2014, trials were conducted with three UK energy retailers and in 2015 the associated spin out was acquired by Quby.
- An on-line game, Apocalypse of MOP, developed to explore understandings of provenance. To date it has attracted over 850 users resulting in over 100,000 logged provenance activities.
- FigureEnergy: a system for better understanding and analysis of home energy data, used by over 30 homes in a trial in collaboration with Kingston University, London.
- The CrowdScanner system was developed for, and won, the US State Department's TAG challenge for social mobilisation and rapid information gathering. This involved five individuals roaming the streets of New York City, Washington DC, Bratislava, Stockholm, and London on a single day and the challenge was to locate them based only on a single photo of each individual released at 8am.
- Squadguru (squadguru.com): an automated fantasy football manager that has outperformed 2.5M players in the online Fantasy Premier league. This has been developed into the RateMyTeam app, which currently has 1,000 views per day.
- The OutrunCancer platform: launched to evaluate networked incentive schemes in collaboration with Cancer Research UK. This attracted over 1,500 participants.
- Veri.ly: a web application that tasks volunteers with verifying reports from the ground or on-line during major disasters. A recent pilot over two days attracted 70 participants and hundreds of visitors.
- SmartThermo and AgentB: demand response prototypes that have been deployed in over 50 homes in and around Southampton to trial agent-based thermal and appliance-based demand response systems that react to real-time prices and impact on the comfort of their owners. These systems led to the follow-on project on the Autonomous Internet of Things.
- GalaxyZoo (www.galaxyzoo.org): The IBCC algorithm was implemented in GalaxyZoo to track user performance and expose them to tasks to help them improve their ability in tagging images.
- The Provenance Service: a suite of tools to help developers implement the W3C standard for provenance tracking in their applications.
- SharedTask App: a crowdsourcing app that aims to classify tweets. Developed in collaboration with Microsoft Research, it won the SharedTask challenge at HCOMP 2013 (crowdsourcing at scale).
- Hire and Fire for TREC: a crowdsourcing app that came second at the TREC crowdsourcing challenge 2012. The app integrates a Hire and Fire algorithm based on IBCC. It allows a recruiter to detect trustworthy and capable workers (that may get tired over time) in order to classify a variety of documents.



What are the remaining challenges?

The broad range of applications deployed within the ORCHID programme helped identify a number of theoretical and practical research questions that remain and will need to be addressed in more specific research endeavours. In particular, the following open research challenges remain:

- How to build HACs that involve multiple humans and multiple agents such that decisions made by agents are understandable to their human counterparts? Also, how should the system (e.g., Internet-of-Things or multi-UAV applications) assimilate human input without impacting on the performance of autonomous actors?
- What theoretical guarantees can be provided for systems that allow humans to intervene in an optimisation process undertaken by agents?
- How should interactions be designed between collectives of humans or agents having diverging objectives or selfish motives?
- How should interactional arrangements of humans and agents be set up to ensure that humans maintain control over the actions taken in the system without over-burdening them with granular decisions-making needs?
- How should incentives be shaped to encourage human participants to contribute to social initiatives (as in disaster response or citizen science) and how can such incentives be calculated by agents?



Research Impact

ORCHID achieved research impact successes across UK industry, the charitable and voluntary sectors, and governmental organisations. These successes were a result of: (a) grounding ORCHID research in real-world problems and applications and (b) delivering ORCHID research outputs (algorithms, software and demonstrations) in a form that could be readily matured, integrated and deployed by system developers and end-users. Practically, these successes were achieved in a number of effective ways, in particular through: partnerships and collaborations; application-focused events and workshops; internships; sharing of code, data, tools and techniques; and commercialization activities. This section highlights a sample of the Knowledge Transfer successes in each of the main areas noted above, also refer to Appendix B for more details.

Partnerships and Collaborations

- ORCHID's partnership with BAE Systems resulted in: transfer of classifier combination technology into the cyber application domain; a secondment to exploit ORCHID technology in the energy domain; joint work to deliver novel human mobility algorithms into MOD and the law-enforcement agencies; and engagement around use-cases for HAC technology in UAV scenarios.
- ORCHID's partnership with Rescue Global (RG) resulted in: steer on disaster response scenarios and requirements; participation in field trials and related ethnographic studies; delivery of crowdsourcing-based predictive analytics technology to RG in support of their operations in Nepal following the 2015 earthquake; joint work on the design and build of an augmented bird-table to assist and improve RG's operational planning.
- ORCHID's collaboration with Hampshire County Council resulted in: a real use-case for HAC technology to support evacuation planning in the event of an emergency at the Fawley Oil Refinery; the design and build of a crowdsourcing platform to incentivise the public to draw building outlines and egress routes on maps of the suburban areas around Fawley; the application of HAC technology to filter, fuse, validate and verify the crowdsourced data.
- ORCHID's collaboration with the Centre for Sustainable Energy (CSE) resulted in: a joint project, funded by EPSRC (*CharloT: Leveraging the Internet of Things to Reduce Fuel Poverty*), in which ORCHID performed ethnographic studies of CSE's energy advisors, focusing on how energy advice is given during home visits to support people in fuel poverty.

Events and Workshops

- ORCHID hosted two Industry Days, drawing attendance from around twenty different organisations to discuss and debate HAC applications in industry.
- ORCHID demonstrated research at a number of external events, organized by academia (e.g., AAMAS), industry (e.g., ASUR), the research councils (e.g., AIS), government (e.g., DSTL's CCS Showcase), and charities (e.g., the BSA's British Science Festival).
- ORCHID participated in Angel Thunder 2014 – the world's largest and most comprehensive inter-agency series of search and rescue exercises. ORCHID conducted ethnographic research studies, enabled by access to Rescue Global's operational meetings, pre-, during and post-operations.

- ORCHID supported several student-led events and HACathons, to share expertise as well as develop 'soft skills' of direct relevance to the project.
- ORCHID held its final Showcase at the Royal Academy of Engineering in September 2015. This all day event included an exhibition of ORCHID technologies, academic presentations and an evening panel discussion chaired by Regius Professor Nick Jennings. It was attended by leading academics and industrialists, generating significant press coverage.



Internships

- Sam Miller was an intern with BAE Systems, applying multi-agent techniques to optimize a parametric model used to predict stress experienced at various locations on Eurofighter Typhoons.
- Davide Zilli was an intern with Microsoft Research Lab working on open hardware for bioacoustics classification and then with MIT's Senseable City Lab working on pervasive systems for the urban space.
- Matteo Venanzi was an intern with Microsoft Research Lab and Bing working on data quality, data aggregation, and crowdsourcing software.
- Alexandros Zenonos was an intern with Toshiba Research Lab, developing a mood recognition framework that utilises wearable sensors data.

Code & Data Sharing

- ORCHID released its Independent Bayesian Classifier Combination software into the Zooniverse project to improve the aggregation of crowdsourced data from volunteer citizen scientists.
- ORCHID released its community-based crowdsourcing module into Microsoft's Infer.NET tool that automatically generates large-scale inference code for Bayesian graphical models.
- ORCHID released its Non-Intrusive Load Monitoring Toolkit, an open-source toolkit for evaluating energy disaggregation techniques.
- ORCHID released its provenance research software into the Prov Python library (46,000 downloads) and the ProvStore, a public online repository for provenance documents.

Commercialisation

- ORCHID research in smart energy led to a spin-out (Joulo) that harnesses smart energy monitoring technology to deliver insight into heating systems, allowing customers to save money on their energy bills and make their homes more comfortable. Joulo was tipped as the UK's brightest home tech startup when it won first place at the 2013 British Gas connecting homes competition. Joulo was recently acquired by Quby, Europe's leading developer for smart thermostats and energy displays.

Collaborations and People

This section draws directly from an independent report, conducted by Daniel Clay Research, and commissioned by ORCHID in 2015 (<http://www.orchid.ac.uk/orchid-case-study/>).

The importance of collaboration was recognised right from the start of ORCHID with lead investigators working closely to understand how, for example, one person's work in algorithms relates to someone specialising in human-computer interaction, and how terminology is used, or research questions interpreted, across different fields. As well as helping to build a common language and understanding, these activities helped to spark ideas of ways in which these different fields could complement one another.

“This collaborative effort culminated in the development of a significant ORCHID demonstrator centered on disaster response. It involved a number of people coming together to build tools for information visualization that used the machine learning expertise from Oxford, the visualization expertise from Nottingham and the agent-based technologies from Southampton. The individual components of the demonstrator were built collaboratively.”

Professor Alex Rogers (University of Southampton)

The success of ORCHID as a whole, was in a large part seen to be down to the way in which researchers worked together, and in the way in which this collaboration was fostered. Established researchers were encouraged to take ownership over mini-projects that all fed into one another and had the remit to bring in other researchers as needed to support the project team. Early career researchers across universities were also empowered to develop both ideas and relationships through meeting independently of senior researchers and immersing themselves in each other's work.



“Completing my PhD as part of the ORCHID project dramatically increased the impact of my research. I particularly enjoyed the internship programme, as I participated as both an intern and as a mentor after finishing my PhD. The opportunity to attend international events, such as summer schools, workshops and conferences, allowed me to build a firm basis of knowledge while also establishing my reputation within my field. I also made full use of the project's industry contacts, starting with my external internship at PlotWatt (an energy analysis start-up in the USA) during my PhD, but also extending into my post-doc with knowledge transfer projects with Telekom Malaysia, British Gas and the Metropolitan Police. Besides my research, I also had the opportunity to participate in a number of outreach events, such as the Southampton Science and Engineering Day and the British Science Festival.”

Dr Oliver Parson (University of Southampton)

Through work across the different application domains of disaster response, future energy systems and citizen science, ORCHID has helped to develop software and processes that have both enhanced theoretical understanding of HACs and the practical application of this learning. ORCHID researchers have submitted a number of successful joint funding bids with industry partners, for example the Ministry of Defence's Centre of Defence Enterprise in collaboration with BAE Systems (see Appendix B for details of all follow-on grants).

“It is not just about knowledge transfer to a new partner. It’s actually knowledge co-development. They are working on shared needs and shared drivers.”

Dr Diane Howard (EPSRC)

There are six patents developed using ORCHID technologies in which ORCHID researchers and industry partners are joint inventors (see Appendix B for full details). Moving from theory to application, in the real world, has been a major success of the ORCHID project.

“It’s well understood that there exists a technology readiness gap. In other words, getting research into real products and systems isn’t trivial. You can do the research in the universities and build demonstration systems, but getting the research into those systems is difficult. In ORCHID we’ve gone a long way to close that technology readiness gap.”

Dr David Nicholson (BAE Systems)

Participating in the ORCHID project has also had a notable influence on the research teams themselves. Through working in close collaboration with academics from other fields as well as industry partners, members of the research team reflected how this has helped to shape and further develop programmes of research outside of the ORCHID project.

“ORCHID opened our eyes and changed the way we thought about human intelligence within a machine intelligence environment. Hitherto I’d seen machine intelligence as devoid of human input and now I see it as human machine intelligence. This was a really profound and incredibly interesting change.”

Professor Steve Roberts (University of Oxford)

The legacy of ORCHID project will be one of having significantly advanced our understanding of HACs. Before ORCHID there were no tangible theories or a detailed understanding of how HACs might be produced, how they might work, nor what the methodological dynamics to work with them effectively might be. ORCHID has deepened the theoretical understanding of how human intelligence and machine intelligence can evolve ‘dynamically, responsively and symbiotically’ to solve the key challenges facing both society and industry.

Another part of the ORCHID legacy is the successful collaboration that was fostered among researchers from very different fields of expertise, and between academia and industry. ORCHID has facilitated new relationships from which tangible advancements have been made in HACs, and through which it is expected that further transformation of blue sky thinking into real innovation will be achieved,

“The things that I am most proud of in ORCHID are those moments where we’ve put bits of work together that wouldn’t normally be together. We’ve achieved success by winning major prizes across different disciplines. Why we’ve done that is because we worked together. We’ve produced a generation of researchers who can do that. That is the most powerful legacy.”

Professor Tom Rodden (University of Nottingham)

APPENDIX A — LIST OF HAC APPLICATIONS

Name	Description	Reference Description
Apocalypse of MOP	Provenance game to investigate people's manipulation and understanding of provenance data.	apocalypseofmop.com
AtomicORCHID	Mixed-reality game to investigate coordination in disaster response. The scenario involves having a planner agent guiding rescuers to complete tasks in teams.	<p>hacplanning.org</p> <p>https://vimeo.com/89728028</p> <p>Ramchurn, S.D. et al. (2015) "Human-agent collaboration for disaster response" JAAMAS.</p>
SmartThermo/ AgentB	HAC application to help evaluate interfaces for demand-response in homes. An agent advises users as to when it is cheapest to schedule their washing machine loads and notifies them if prices change.	Costanza, E. et al. (2014) "Doing the Laundry with Agents" CHI.
AgentSwitch	Personalised energy tariff-recommender system. Incorporates a prediction algorithm for yearly energy consumption and disaggregation of energy feeds.	<p>agentswitch.com</p> <p>https://vimeo.com/50979888</p> <p>Ramchurn, S.D. et al. (2013) "AgentSwitch: towards smart electricity tariff selection" AAMAS.</p>
Augmented Bird-table	An interactive system that uses computer vision and projections and can be used with any physical map. It provides organisations, decision makers and responders with the tools and information they need, to more effectively and efficiently save lives and respond to disasters.	<p>https://vimeo.com/132845564</p> <p>https://vimeo.com/119224456</p> <p>Fischer, J.E et al (2015) "Building a Birds Eye View: Collaborative Work in Disaster Response". CHI.</p>
Cicada App	Android and iPhone app to detect insects in the New Forest.	<p>newforestcicada.info</p> <p>Zil, D.li et al (2014) "A hidden Markov model-based acoustic cicada detector for crowdsourced smartphone biodiversity monitoring" JAIR.</p>
CollabMap	Crowdsourcing platform to help create high resolution evacuation maps through gamified processes.	<p>www.collabmap.org.</p> <p>Ramchurn,S.D. et al (2013) "CollabMap: crowdsourcing maps for emergency planning" ACM Web Science.</p>
Crowdscanner	App that won the TAG challenge. Using monetary incentives, the app was able to gather a large team of contributors to identify individuals in 4 cities across the world.	<p>https://vimeo.com/56720221</p> <p>Rahwan, I. et al. (2012) "Global manhunt pushes the limits of social mobilization" IEEE Computer</p>
SquadGuru/ Fantasy Football	Algorithm for sequential decision making in the fantasy football domain.	<p>www.squadguru.com</p> <p>Matthews, T. et al. (2012) "Competing with humans at fantasy football: team formation in large partially-observable domains" AAAI.</p>

Name	Description	Reference Description
Figure Energy	Web application that provides an interactive interface to a home's electricity consumption.	http://vimeo.com/42328926 Costanza, E. et al. (2012) "Understanding domestic energy consumption through interactive visualisation: a field study" UBICOMP.
GalaxyZoo	Crowdsourcing classification of astronomical objects. The IBCC is used to help understand types of users in the system and avoid them getting bored or improve their performance by sending them tasks that fit the purpose.	E. Simpson et al. (2011) "Bayesian combination of multiple, imperfect classifiers" NIPS workshop.
Hire and Fire	IBCC applied to crowdsourcing to untrustworthy workers. The algorithm detects the bad workers and fires them. It also hires new workers and keeps them in if it needs more information.	working paper based on TREC challenge work (see below)
HAC-ER	A prototype disaster response system that comprises a multi-UAV coordination system, a crowdsourcing component to gather information from inhabitants of an affected area and create heatmaps of the disaster zone, the AtomicORCHID coordination component, and a provenance tracking tool.	https://vimeo.com/119525848 Ramchurn et al. (2016). "Human-agent collaboration for disaster response." Journal of Autonomous Agents and Multi-Agent Systems.
Outrun Cancer	Incentive mechanisms for engaging people in crowdsourcing activities. Project was carried out in partnership with Cancer Research UK.	https://vimeo.com/89677056 http://outruncancer.co.uk/
Provenance Service	Suite of python modules providing: an implementation of W3C PROV Data model with JSON import/export support; a light-weight provenance tracker for recording provenance (in python code); a provenance repository service that provides a REST API for storing/retrieving provenance and a Web interface for browsing the repository's content.	http://www.w3.org/2011/prov/wiki/Main_Page Moreau, L. and Groth, P.T. (2013) "An Introduction to PROV" Morgan & Claypool Publishers
SharedTask BCC App	An algorithm developed in collaboration with MSR to classify tweets that won the SharedTask Challenge at Crowdsourcing at Scale competition at HCOMP 2013	https://crowdfunder.com/blog/2013/12/crowdsourcing-at-scale-shared-task-challenge-winners/
TariffAgent	App to simulate real-time energy tariffs and to evaluate human-agent interaction for tariff switching on a daily basis in the face of uncertain prices.	Alan, A. et al. (2014) "Mixed-initiative electricity tariff switching for dynamic environments" AAMAS.
Text Retrieval Crowdsourcing Challenge	A challenge as part of the Text Retrieval Conference run by NIST. The 'Crowdsourcing' challenge requires the use of crowdsourcing to help match topic-document pairs. The approach taken by the Soton-Oxford team involved the use of IBCC (Independent Bayesian Classifier Combination) and an Amazon Turk Deployment.	https://vimeo.com/89262971 Simpson, E., et al. (2013). Using a Bayesian Model to Combine LDA Features with Crowdsourced Responses. In , the Twenty-First Text REtrieval Conference (TREC 2012)
Ver.ily	Web application that tasks volunteers with verifying reports from the ground or on-line during major disasters.	http://veri.ly/

APPENDIX B — KEY MEASURES OF SUCCESS

Research Quality

- Number of publications: 252
 - 62 journal articles
 - 177 conference papers
- Number of citations: 4552
- Prizes and Awards (including best papers): 24
 - AAMAS 2015 Best Applications Paper – Ramchurn et al
 - ICICA 2014 Best paper – Levenberg et al
 - Buildsys 2014 Best Demo 2014 – Parson et al
 - World 3rd in International Microelectronics Competition 2014 - Beck
 - Winner Google Impact Challenge 2014 – Roberts et al.
 - WWW 2014 Best Paper Runner-up - Venanzi et al
 - BuildSys 2013 Best Paper - Rogers et al.
 - Winner HCOMP 2013 Crowdsourcing at Scale Shared Task Challenge - Venanzi et al
 - Winner 2013 British Gas Connecting Homes Start-up Competition – MyJoulo
 - EPSRC Doctoral Award 2013 – Parson
 - UbiComp 2013 Best Paper (Honourable Mention) – Luger
 - IJCAI 2013 Outstanding Student Paper - Zilli and Parson
 - CHI 2013 Best Paper - Rodden et al
 - Dean's Award for Research Excellence University of Southampton 2013 – Rahwan
 - AAMAS 2013 Best Student Paper Award – Alam et al
 - BCS Distinguished Dissertation Award (honourable mention) – Tran-Thanh
 - ECCAI 2012 Artificial Intelligence Dissertation Award (honourable mention) – Tran-Thanh
 - Runner-up TREC Challenge 2012 – Simpson et al
 - Winner TAG Challenge 2012 – Naroditskiy et al
 - AAAI 2012 Honourable Mention Award – Tran-Thanh et al
 - ECAI 2012 Nomination Best Student Paper Award –Tran-Thanh et al
 - IEEE International Conference on Data Mining 2012 Best paper award - Reece et al
 - NIPS 2012 Workshop on Human Computation for Science and Sustainability Best Contribution Award - Simpson et al

Research Impact

- Collaborations formed with academic groups outside ORCHID: 25
 - Hans Fangohr, CDT in Next Generation Computational Modelling, Southampton Uni.
 - Niki Trigoni, CDT in Autonomous Intelligent Machines and Systems, Oxford University.
 - Sven Seuken, University of Zurich
 - Ruth Retie, Kingston Business School
 - Mike Hazas, Lancaster University
 - James Scott, Microsoft Research
 - Abigal Sellen, Microsoft Research
 - Keith Edwards, Beki Grinter, Georgia Tech
 - Kathy Willis, Oxford Biodiversity Institute, Kew Gardens
 - Derek McAuley, Horizon
 - Mario Berges, Carnegie Mellon University
 - Mark Girorlami, UCL,
 - Muffy Calder, Glasgow University
 - Kepler pipeline team, NASA
 - Prof Rob Fender, University of Oxford (LOFAR & SKA)
 - Tao Qin, Microsoft Research Asia
 - Peter Key, Microsoft Research Cambridge
 - Botond Szabo, CREST Paris
 - Jia Yuan Yu, IBM Research Dublin
 - Suzanne Aigrain, Exoplanet research group, Oxford
 - Aris Karastergiou, Radio Astronomy group, Oxford
 - Marian Dawkins, Animal Behaviour Group, Oxford
 - Ioannis Psorakis, Doyne Farmer, Institute for New Economic thinking, Oxford
 - Simon Benjamin, Quantum Computing Group, Oxford
 - Interaction Design, Chalmers University of Technology, Gothenburg, Sweden
 - Systems Group University of Cambridge
 - Warwick Management Group
 - Edinburgh School of Design
 - Royal College of Art

- Invited Keynotes: 12

○ NCSML workshop 2015	Steve Roberts
○ ICAART 2015	Nick Jennings
○ Big Data, Big Models, Big Deal - CSML 2014	Steve Roberts
○ MaxEnt 2013	Steve Roberts
○ ECML 2013	Steve Roberts
○ EPSRC student future workshop	Tom Rodden
○ AAMAS HADM 2013 workshop	Tom Rodden
○ AAMAS 2012	Alex Rogers
○ Computational Sustainability 2012	Alex Rogers
○ UKRC Digital Economy All Hands Meeting 2012	Alex Rogers
○ Royal Society “time series modelling for physical sciences”	Steve Roberts
○ NIPS workshop on crowdsourcing 2012	Steve Roberts

- Workshops in Major Venues: 24

○ Massive MAS, 2015	Long Tran-Thanh
○ HAIDM, AAMAS 2015	Gopal Ramchurn
○ Ubicomp 2014	Tom Rodden/Ewa Luger
○ HAIDM, AAMAS 2014	Gopal Ramchurn
○ NordiCHI 2014	Joel Fischer
○ RSS 2014	Steve Roberts
○ Provenance Week 2014	Luc Moreau
○ IPAW 2014	Luc Moreau
○ Provenance Analytics Workshop 2014	Luc Moreau/Dong Huynh
○ Sigcomm 2013	Tom Rodden
○ Ubicomp 2013	Tom Rodden
○ AMEC 2013	Seb Stein
○ NIPS 2013	Mike Osborne
○ HAIDM, AAMAS 2013	Gopal Ramchurn
○ OPTMAS 2013	Gopal Ramchurn
○ ATES, AAMAS 2013	Alex Rogers
○ ECSCW 2013	Joel Fischer
○ ATES, AAMAS 2012	Alex Rogers
○ NIPS 2012	Mike Osborne
○ NCAF 2012	Steve Roberts
○ TADA/AMEC 2012	Seb Stein
○ HAIDM, AAMAS 2012	Gopal Ramchurn
○ OPTMAS 2012	Gopal Ramchurn
○ OPTMAS 2011	Gopal Ramchurn
○ ATES, AAMAS 2011	Alex Rogers

- Research Visits from other organisations to work with ORCHID: 23

○ Filippo Bistaffa	University of Verona, Verona, Italy
○ Sofia Ceppi	Politecnico di Milano, Italy
○ Renzo de Nardi,	UCL, UK
○ Mathijs de Weerd	TU Delft, The Netherlands
○ Geradline Fitzpatrick	University of Vienna, Austria
○ Keiichiro Hayakawa	Toyota Central R&D labs
○ Francois Jean	ENSTA-Bretagne, France
○ Marina Jirotko	University of Oxford, UK
○ Marc Langienrich	University of Lugano, Switzerland
○ Fabio Maffioletti	University of Verona, Verona, Italy
○ Areej Malibari	King AbdulAziz University, Saudi Arabia
○ Robert Niven	CarbonCure
○ Toni Penya-Alba	IIIA – CSIC, Spain
○ Riccardo Reffato	University of Verona, Verona, Italy
○ Avi Rosenfeld	Jerusalem College of Technology, Israel
○ Simo Sarkka	Aalto University, Finland
○ Mike Shann	University of Zurich, Switzerland
○ Arfon Smith	Adler Planetarium, Chicago, US
○ Piotr Szczepanski	Warsaw University of Technology, Poland
○ Mike Twidale	University of Illinois, US
○ Twan van Laarhoven	Radboud University, Nijmegen, The Netherlands
○ Ioannis Vetsikas	IIT Demokritos, Greece
○ Yair Zick	Nanyang Technological University, Singapore

- Extended visits by ORCHID researchers to other organisations: 10
 - Internship at Toshiba 2015 Alexandros Zenonos
 - Internship at MSR 2014 Matteo Venanzi
 - Internship at MSR 2014 Davide Zilli
 - Internship at MIT 2014 Davide Zilli
 - The Moller-Maersk Institute 2013 Gopal Ramchurn
 - University of Southern California 2013 Gopal Ramchurn
 - Internship at MSR 2013 Matteo Venanzi
 - Internship at PlotWatt 2013 Oliver Parson
 - Internship at BAE Systems 2013 Sam Miller
 - University of Verona 2012 Gopal Ramchurn
 - Internship at PlotWatt 2012 Oliver Parson

- Software and standards released: 10
 - Latent force software accompanying JMLR article (<http://jmlr.csail.mit.edu/papers/v15/>).
 - Smart Home Network (<http://www.smarthomeframework.org/>).
 - NILMTK: An Open Source Non-intrusive Load Monitoring Toolkit (<https://github.com/nilmtnk/nilmtnk>).
 - Literatin a plug-in allows users to explore the complexity of any text found within a webpage. (<https://chrome.google.com/webstore/detail/literatin/igpbgnfcceidjgcjddcdamjgbpdcmbnl?hl=en-GB>).
 - Infer.NET Community-based Bayesian Classifier Combination (<http://research.microsoft.com/en-us/um/cambridge/projects/infernet/>).
 - Underpinning machine learning software developed for ORCHID-funded mobility analysis work (<https://pypi.python.org/pypi/vbihmm/>).
 - PROV Standard (<http://www.w3.org/TR/prov-overview/>).
 - ProvToolbox (<http://lucmoreau.github.io/ProvToolbox/>).
 - ProvStore (<https://provenance.ecs.soton.ac.uk/store/>): a public online repository for provenance documents.
 - Prov Python library version 1.1.0 (<https://pypi.python.org/pypi/prov/>).

Industrial Impact

- Number of technologies pulled through: 8
 - Cicada app and analysis expanded and applied by Centre for Ecology and Hydrology to cover all UK ophoptera.
 - Human mobility analysis technology applied by BAE Systems in security and counter-terrorism context.
 - DEMS (Portsmouth BAE): implemented algorithms to monitor and control loads in micro grids.
 - IBCC technology applied by BAE Systems in context of Cyber and Aircraft fault classification.
 - PyIBCC software supplied to Zooniverse for use with citizen science projects (planet hunters, snapshot Serengeti, space warps).
 - Crowdsourcing Module developed with Microsoft Research being tested on an experimental platform used by Bing researchers prior to further development and application.
 - Joulo Ltd founded. Licensing analysis algorithms from the University of Southampton. Acquired by Quby early 2015.
 - AgentSwitch spin off in progress. Working with Hampshire County Council for community energy purchasing programme.
- Patents/Licenses given out: 6
 - “Crowdsourcing System with Community Learning”, Inventors: Matteo Venanzi, John Guiver, Gabriella Kazai, Pushmeet Kohli, Milad Shokouhi, MS 340522.01.
 - “Adaptive Task Assignment”, Inventors: Matteo Venanzi, John Guiver, Pushmeet Kohli, MS355469.01.
 - “Sensor Data Processing”, Inventors: Reece, Roberts and Lloyd (Oxford) and Nicholson (BAE), Patent No: PCT/GB2012/000481.
 - “A method for inferring an output distribution using a Gaussian Process (on kernelised data)”, Inventors: Reece, Roberts and Lloyd (Oxford) and Nicholson (BAE) Patent No: GB1109209.5.
 - “A method for inferring a relevance for a data source using a regression technique (on kernelised data), Inventors: Reece, Roberts and Lloyd (Oxford) and Nicholson (BAE), Patent No: GB1109210.3.
 - “A method for inferring the relevance for a pre-processing technique using machine learning”, Inventors: Reece, Roberts and Lloyd (Oxford) and Nicholson (BAE) Patent No: GB1109206.1.
- Number of external organisations engaged with: 42
 - including the Australian Centre for Field Robotics, BAE Systems, BBC, Cancer Research UK, Centre for Ecology and Hydrology, Department of Energy and Climate Change, DSTL, Envitia, Google, Home Office, Kiwi Power, Microsoft, PlotWatt, QinetiQ, Rescue Global, Secure Meters Ltd, Toshiba Research Lab, Toyota Central R&D Labs and Ushahidi.

Outreach

- Media mentions: 102
 - including the BBC, New Scientist, The Guardian, The Daily Telegraph, Government Gazette, Crisis Response Journal, Electronics Weekly, WIRED and The Economist.
- Deployments of trial systems (number of participants, as of Jan 2016)
 - MyJoulo 2245 users
 - Cicada 5000 users
 - AgentSwitch 3000 users
 - AtomicORCHID 82 users
 - TariffAgent 20 users
 - Apocalypse of MoP 850 users
 - Outrun Cancer 1577
 - Veri.ly 70 users
 - Demand Response System (Agent B) 20 users
 - Fukushima Heatmap 7,064 page views
 - SmartThermo 30 homes over 1 month.
- Demonstrations and presentations at public events: 17

Demo/Presentation	Where	When
Disaster response/Smart Energy/Citizen Science HACS	ORCHID Showcase, London	2015
Disaster response	British Science Festival, Birmingham	2014
New Forest Cicada	The Wood Fair, New Forest	2014
ORCHID Industry Day	London	2014
Autonomous Systems	Southampton	2014
HACs in the Smart Grid	Webinar	2013
Disaster response	First Lego League Event	2013
New Forest Cicada	BBC Summer of Wildlife, Birmingham	2013
New Forest Cicada	British Science Festival, Newcastle	2013
I'm a Scientist...	Online	2013
ORCHID Industry Day	Farnborough	2013
New Forest Cicada	Big Bang Fair, Solent Region	2013
New Forest Cicada	University of Southampton Science and	2013
ORCHID Overview	Big Bang Science and Engineering Fair,	2012
ORCHID Overview	Farnborough Air Show	2012
AtomicORCHID	University of Southampton Open Day	2012
CARGO	igFest, Bristol	2012

- Master classes, learning and classroom materials provided: 10
 - NILM 2014 and 2015: European venue for discussing non-intrusive load monitoring research from industry and academia
 - Researcher Links Workshop for British Council on Disaster Response (Mexico).
 - Incentive mechanisms for electric vehicle charging for Toyota Central R&D Labs.
 - Designed a learning activity and video based on Outrun Cancer for the University of Southampton MOOC on Digital Marketing.
 - Training course on energy disaggregation for Telekom Malaysia R&D & iTG.
 - Police Workshop on Provenance (NCA, South East Regional Cyber Crime Unit).
- Videos produced: 26

Title	url
ORCHID Case Study (2015)	https://vimeo.com/139907558
ORCHID HAC-ER video (2015)	https://vimeo.com/119525848
Augumenting the Bird-table (2015)	https://vimeo.com/132845564
Multi-UAV Coordination for Disaster Response (2015)	https://vimeo.com/134088080
Building a Birds Eye View: Collaborative Work in Disaster Response (2015)	https://vimeo.com/119224456
Atomic ORCHID: Team coordination in disaster response (2014)	https://vimeo.com/89728028
Human-Agent Collaboration for Multi-UAV Coordination (2014)	https://vimeo.com/76869219
Energy Management Overview (2014)	https://vimeo.com/88777062
Minimising Queues at Electric Vehicle Charging Stations (2014)	https://vimeo.com/72832240
Human-Agent Collectives: The Power of the Crowd (2014)	https://vimeo.com/108577779
OutrunCancer (2014)	https://vimeo.com/89677056
TREC crowdsourcing challenge (2014)	https://vimeo.com/89262971
Making the most of citizen science (2014)	https://youtu.be/KntYMzDKY9I
Disaster Response Overview (2013)	https://vimeo.com/76205207
Flexible Control and Agile Teaming of Unmanned Systems in Disaster Response (2013)	https://vimeo.com/62688684
Coalition Formation (2013)	https://vimeo.com/57623609
Online Mechanism Design for Electric Vehicle Charging (2013)	https://vimeo.com/56767564
The Future with Energy-Management Agents (2013)	https://vimeo.com/50979888
FigureEnergy (2013)	https://vimeo.com/42328926
Home Energy Management (2013)	https://vimeo.com/35583736
Non-intrusive Load Monitoring for Home Energy Management (2013)	https://vimeo.com/55600196
An Intelligent Agent for Home Heating Control (2012)	https://vimeo.com/18456097
Predicting Human Mobility Patterns (2013)	https://vimeo.com/57623608
Trust-Based Learning Methods for Crowdsourced Radiation Monitoring in the Fukushima Disaster (2013)	https://vimeo.com/56863480
TAG Challenge (2013)	https://vimeo.com/56720221
Zooniverse Labs (2013)	https://vimeo.com/59410864

Research Capacity Building

- Number of PhDs graduated: 13
 - Wenchao Jiang 2015 Nottingham
 - Obaid Malik 2015 Southampton
 - Sasan Maleki 2015 Southampton
 - Jan-Peter Calliess 2014 Oxford
 - Ewa Luger 2014 Nottingham
 - Matteo Venanzi 2014 Southampton
 - James McInerney 2014 Southampton
 - Sam Miller 2014 Southampton
 - Oliver Parson 2013 Southampton
 - Muddasser Alam 2013 Southampton
 - Edwin Simpson 2013 Oxford
 - Oleksandr Pryymak 2013 Southampton
 - Francesco Delle Fave 2012 Southampton

- Research Fellows appointed to faculty positions: 7
 - Long Tran-Thanh 2015 University of Southampton
 - Joel Fischer 2015 University of Nottingham
 - Nadia Pantidi 2014 University of Cork
 - Feng Wu 2014 University of Science and Technology of China
 - Talal Rahwan 2014 Masdar Institute of Technology
 - Sebastian Stein 2013 University of Southampton
 - Michael Osborne 2012 University of Oxford

- Research interns employed on ORCHID: 15
 - Jack Walker 2015
 - Rinesh Patel 2015
 - Dennis Parchkov 2015
 - Quan Tran 2014
 - Jack Flann 2014
 - Sam Millar 2013 & 2014
 - Po Ting Tse 2013 & 2014
 - Quan Tran 2013
 - Alex Botev 2013
 - Debanjan Ghosh 2012
 - David Smith 2012
 - Andrei Petre 2011 & 2012

- Number of follow on grants: 30

Grant Name	Funder	When	Where	Value(£k)
Learning to Trust the Crowd	CDE	2016	Oxford/BMT Defence Services Ltd/Rescue Global	100
Mixed reality game pattern cards	Nottingham Impact Accelerator Fund	2016	Nottingham	10
Design by Privacy	Microsoft	2015	Nottingham/New York/Microsoft Research	50
Cyber security solutions for smart traffic control systems	EPSRC	2015	Southampton/ Nanyang Technological University	500
Future Everyday Interaction with the Autonomous Internet of Things	EPSRC	2015	Southampton	806
Aperio: Low cost façade management in naturally ventilated buildings	EPSRC	2014	Southampton/CSE/ Open System solutions Ltd/Local authorities	494
Adaptive Demand Response	TSB	2014	Southampton/ KiwiPower	250
Researcher Links Workshop Grant for Disaster Response (Mexico)	British Council	2014	Southampton	50
Casma: Citizen-centric approaches to Social Media analysis	ESRC	2014	Nottingham	500
Humbug: Biosound/Mosquito sensor project	Google	2014	Oxford/ Southampton	500
Intelligent SME energy management and trading with ancillary services.	EPSRC / TSB	2014	Southampton	200
Thermal Modeling and Inference with HomeOS	EPSRC / MSR	2014	Southampton	60
ASUR: Human-Agent Collaboration for Multi-UAV Control	DSTL	2014	Southampton	50
Energy systems KTS with BAE Systems	EPSRC	2014	Southampton/ BAE Systems	50
CharloT: Leveraging the Internet of Things to Reduce Fuel Poverty	EPSRC	2014	Southampton/ Nottingham/ CSE	277
Human Mobility Analysis and Anomaly Detection	CDE	2013	Southampton/ BAE Systems	77
Creating the energy for change	EPSRC	2013	Southampton/ Nottingham	1076
ORCHID Artist in Residence	Leverhulme Trust	2013	Southampton	15
Domestic energy management	HEIF Fund	2013	Southampton	15

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Follow on Grant	Funder	When	Where	Value(£k)
Referral incentives in crowdsourcing	British Academy	2013	Southampton	8
Referral incentives in crowdsourcing	FSHS Strategic Interdisciplinary Research	2013	Southampton	7
Transforming Feedback –Interactive, Practice-level Visualisation of Electricity Consumption	Pilot study with Kingston University	2013	Southampton/ Kingston Business School	50
Multiagent collectives for sensing, autonomy, intelligence and control	EPSRC	2013	Southampton	1316
Autonomous behaviour and learning in an uncertain world	EPSRC	2013	Oxford	1200
Prototyping open innovation models for ICT-enabled manufacturing in food and packaging	EPSRC	2013	Nottingham	1827
Home Hub-of-all-Things as platform for multi-sided market powered by internet-of-things	EPSRC	2013	Nottingham	982
User centred networking	EU	2013	Nottingham	3947
Automated assessment of broiler chicken welfare using optical flow patterns in relation to behaviour, disease risk and production	BBSRC	2013	Oxford	738
A robust toolbox for exoplanet analysis	Leverhulme Trust	2013	Oxford	220
BioSound	James Martin	2013	Oxford	225
			TOTAL	15600

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ORCHID was an EPSRC funded Programme Grant, and we gratefully acknowledge their support.

BAE SYSTEMS

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