Innovate UK

ISCF Robotics and Artificial Intelligence in Extreme Environments

Final evaluation — a report from Technopolis and Ipsos MORI

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Ipsos MORI

technopolis group

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Executive summary

The UK government has invested around £112.4m in the Robotics and Artificial Intelligence in Extreme Environments (RAI-EE) programme, as part of the multi-billion pound Industrial Strategy Challenge Fund (ISCF). Additionally, the programme has leveraged around £87.4m in matching funds, including £49.7m in-cash and £30.2 in-kind contributions, mainly from businesses involved in the programme.

Initially, the programme comprised four Use-inspired Research Hubs (as well as extension calls for the RAIN and ORCA Hubs, respectively), with each Hub undertaking a series of work packages and activities within the context of its own grant); and 78 innovation projects across the two strands: Innovation R&D, and Demonstrator programme.

This report presents the Final Evaluation of the ISCF RAI-EE programme, focusing primarily on those activities, following the ‘Evaluation Framework’ set up in 2018, and the ‘Baseline and Process Evaluation’ (2019) and the ‘Interim evaluation’ (2020). It consolidates evidence gathered throughout all the evaluation phases.

Subsequent grants were awarded in 2021 to compensate for delays caused by COVID-19 and maintain programme value, as well as to expand the range of R&D projects to the wider field of Service Robotics. Projects awarded from these grants were broadly classified as COVID Grants and 1-year Extension Funds. A further 67 projects were awarded under the programme extension: 16 projects under the COVID Grants and 51 projects awarded under the 1-year Extension. Additional evidence on those grants have also been collected to inform this final evaluation report.

This Final Evaluation assesses the programme achievements using a mixed-methods approach, which includes analysing secondary data sources, and conducting a longitudinal survey, 10 stakeholder interviews, 16 case studies (12 of them longitudinal) and bibliometric analysis. Whenever possible, a comparison was made between the outcomes of successful applicants and a control group of unsuccessful applicants, to establish a counter-factual scenario and estimate the net effect of the programme.

Below we present the main findings, across the key area of analysis (following the Theory of Change developed for the programme). For each area we marked in green the instances where there is evidence of substantial positive impact, in amber where there is some evidence of positive impact (or less progress), and in red where there is evidence of low to no impact. Finally, we mark in grey the areas where the evidence is inconclusive.

Main findings – RAI in extreme environments

Overall, the findings indicate that the programme has contributed positively to the majority of expected outputs and short-term outcomes, including advancements in academic outputs and the maturity of technologies developed within the projects. Additionally, there have been positive benefit in terms of R&D employment in RAI in extreme environments. Evidence also suggests that support from the programme may have helped to maintain levels of R&D investment in RAI in extreme environments within participating organis-ations (but results need to be taken with caution given number of observations) and attracted private investment from venture capitalists.

There is less progress in terms of commercial-isation and adoption of RAI solutions. This is perhaps expected given the maturity of the technologies supported (which have made progress but are still not close to market) and the time required for these technologies to transition into commer-cialised applications. Other factors hindering commercialisation include barriers to adoption among end-users (due to factors ranging from internal skills to regulatory barriers), as well as the relatively small market opportunities for certain solutions, such as those pertaining to Nuclear and Space industries.

Widening of the UK’s R&D capability and capacity in RAI for extreme and challenging environments

Key –

Improved connectivity between research and industry

- Participant businesses are engaging in more R&D projects with other industry partners – 2.6 more R&D projects on average. This is an increase of approximately one project compared to the baseline, which already included collaboration within the grant.
- 85% of respondents (across all progr-amme strands) believed that programme participation would lead to increased collaboration with end-users, although this percentage represents a slight decline compared to the baseline.
- The User-Inspired Research Hubs engaged with industry to varying degree. One of the most succesful collaborations has been between Sellafied and one of the Nuclear Hubs, specifically for the testing of an autonomous vehicle witin Sellafield sites. It is unclear the extent to which the industrial collaborations developed or advanced under the Hubs will be sustained over time. (ResearchFish data shows that industrial investment has been on the order of £2m so far).

Key –

Improved skills and capabilities

- 94% of participants state that involvement in the programme has led to improved skills and understanding of robotics and AI for extreme environments among researchers and managers in their organisation.
- 94% of participants state that involvement in the programme has led to improved internal capabilities to conduct research into robotics and AI solutions (with 52% saying that this had happened to a great extent).
- Case studies examining collaborative R&D and demonstator projects show that one of the most significant effects to date has been to strengthen the capacity of participant companies. This has enabled them to expand R&D efforts, strenghten their technology roadmaps, extend their networks and access state-of-the-art testing and scientific facilities.

Increased volume of excellent research

- Bibliometric analysis shows that the UK remains one of the main players in the world with respect to the production of scientific knowledge in the area of RAI in extreme environments, in terms of both volume of outputs and citation impact. Its relative international position - on both outputs and citation – has also improved from the baseline (2018).
- The volume of publications emerging from the programme leads to the conclusion that the programme has contributed to sustaining this position.
- The programme has generated a higher number of publications per £m compared to UKRI grants within the same period, based on ResearchFish data (which only includes the Hubs)
- The production of other types of research outputs, such as research materials and databases, has been relatively lower. Additionally, only one Hub reports applying for three patents.

Increased R&D investment in UK RAI-EE

- Evidence suggests that the programme may have played a role in stabilising R&D spending, which could have otherwise experienced a substantial drop, aligning with the overall decline in UK investments in robotics in 2019. However, results need to be taken with caution as slightly different results emerge when analysing different samples of the data.
- There is a decrease in average annual R&D expenditures specifically on RAI in extreme environments, particularly in the final stage among successful applicants (from £2.66m a year on average to £1.48m on average).
- Investments in this area have experienced an even more significant decline among unsuccessful applicants (from £2.02m a year on average to £675k on average).

Increased R&D employment in UK RAI-EE

- There is an increase in R&D employment from the first to the final stage (of between 6 and 8 employees on average).
- The pattern among unsuccessful applicants is less consistent as it changes depending on the cohort analysed. However, in both cases, the level of R&D employment is substantially lower than in comparison with the successful applicants.
- The increase in R&D employment coupled with the decrease in R&D investment may indicate extra mural activity taking place among successful applicants.

Increased private investment in UK RAI-EE

- Evidence suggests that the programme has successfully attracted private investment.
- Using information from Pitchbook we find that by 2023, 131 successful applicants have raised equity funding since 2018, with a total value of just over £1bn, nearly 10 times more in comparison with the baseline position.
- In comparison 95 companies in the control group were reported to have raised equity since 2018, with a total investment value of £85m.

Supporting the development of market ready RAI solutions for extreme environments

Key –

Progress against Technology Readiness level

- Evidence shows that funded projects in CR&D and Demonstrator strands have made some progress in terms of technology readiness level (TRL), and that progress is stronger in comparison with the counterfactual scenario.
- On average, they have progressed by one TRL level (since the point of application) moving from specifying and developing a proof of concept to demonstrating this proof of concept in a test site (with a natural progression from the baseline through the interim and final stage as projects progressed and concluded).
- Unsuccessful projects, in contrast, had remained at the same TRL level on average.

Adoption of RAI solutions (developing and testing solutions)

- The programme has successfully supported the development of more RAI systems and solutions in comparison with the counterfactual scenario.
- We find that successful applicants have on average developed 4.0 new RAI systems and solutions, tested 4.8 and demonstrated 5 to potential customers and end users. This represents a notable increase in comparison with the baseline and interim positions.
- In contrast, the numbers of solutions developed, tested and demonstrated is lower among unsuccessful applicants and has also declined over time.

Adoption of RAI solutions (adoption by end users)

- Evidence of the degree of TRL progression (i.e. still below commercial-isation stage in the majority of cases), relatively low application of RAI systems and readiness to adopt, and of lack of evidence on commercialisation suggest that adoption remains low even at this stage of the programme.

Improved business performance

- Evidence collected via survey shows that successful applicant companies have had a decline in their **average annual turnover** of £0.9m between now and the baseline stage (based on results from a mixed cohort).
- In comparison, unsuccessful applicants have had a decline of £0.8m in **average annual turnover** in the same period of analysis.
- This suggests that the net impact of the programme on turnover is zero or close to zero (-£0.1m, obtained from comparing the change in average turnover among the treatment and the control group).
- The evidence collected via case studies goes in line with the findings from the survey. Here we found that only 3 case studies (out of 12) provide concrete evidence of additional turnover being generated as a consequence of developments supported by the programme.
- It is important to note however, that the survey and case studies do not capture one success case (Wootzano) which in itself accounts for £300m in value of a new contract/deal that could be attributed to the programme. This commercial success is explained in part by funding provided to via the extension grants (see overleaf).

As per our Theory of Change, **societal impacts** are only expected to materialise in the future (following the commercialisation and adoption of solutions developed through the programme). As such, there is no concrete evidence at this stage of societal impact having been achieved. However, our case studies suggest that, in the future, one of the main areas of impact expected concerns the safety of personnel involved in the operation and maintenance of facilities in extreme environments. This would be primarily achieved by replacing humans with autonomous robotic systems, for example in nuclear decommissioning, inspection of offshore assets, and supporting safer and less disrupted railway infrastructure.

The case of Wootzano and its highly dexterous robots for fruit and vegetable packaging could also help reducing problems related to shortage of labour and well as costs (with still unclear effects on net employment).

As reported at the interim stage, there are also some signals of positive spillovers in terms of policy influence, with representatives of various Use-inspired Research Hubs sitting in different committees that are working to provide national and international methodologies and tools for the development, implementation, use, and assessment of robotics and autonomous systems.

Main findings – programme extension to other environments

In 2020, largely in response to the COVID-19 pandemic, a one-year extension was devised to support robotics research in new domains. In contrast to the initially funded core projects, the definition of extreme environments was expanded to include dangerous environments such as those in the construction or agri-tech industries. The funding from the extension round was largely divided into three parts:

- Funding existing ISCF RAI projects that were impacted by the pandemic.
- Resilient future projects that supported projects in new areas, including agriculture, health, logistics and construction.
- COVID-19 fast start projects which were identified as part of Innovate UK's business led response to global disruption competition.

We collected evidence on key indicators for this cohort and found that:

The **programme has leveraged resources in the areas covered by these calls**, with successful applicants spending more on their projects as time has progressed in comparison with unsuccessful applicants. Furthermore, R&D spending in robotics and AI have remained constant among successful applicants but has declined amongst unsuccessful applicants, suggesting that the programme has **protected R&D investment levels**. R&D employment has remained the same across both groups, with a slight increase among successful applicants.

The **programme has also successfully supported progress towards commercialisation**, with a median increase in technological maturity from TRL3 to TRL5 among successful applicants and no change among unsuccessful applicants (based on evidence from the CR&D and Demonstrators). It has supported similar progress among Hubs (at least for some specific products/solutions). Despite this progress, given the TRLs achieved, projects supported by the programme are likely to require additional resources (time, expertise, and financial investment) to further mature to the point of adoption.

Notwithstanding the point above, the evidence also suggests the programme has had a positive impact on turnover related to RAI, with successful applicants experiencing a median increase of £82.5k in comparison with the baseline position. In contrast, unsuccessful applicants experience a median increase of £62.5k in turnover related to RAI. The successful case study mentioned above (Wootzano) was also funded by this extension (as a continuation of an original grant funded via the Innovation Lab).

Lessons learned and recommendations

Programme design

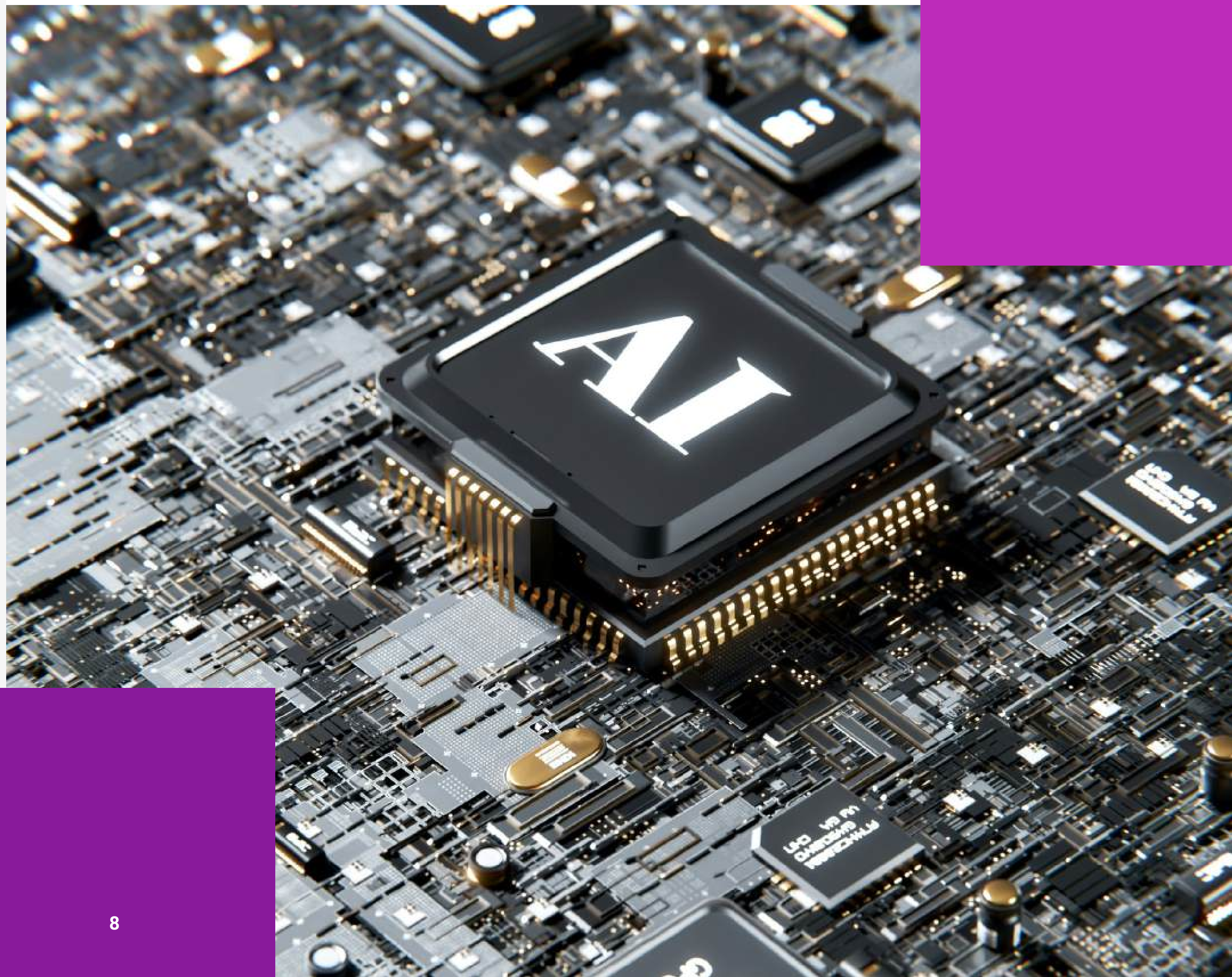
- As suggested in Process evaluation report (2019) future iterations of the programme with a challenge driven approach could consider strengthening cross-fertilisation across strands via dedicated measures (e.g. special call for proposals), understanding the need to maintain a balance between its support for a core group of organisations and the need to remain open to new ideas from outside the mainstream. Evaluations of other ISCF programmes (Audience of the Future, Next Generation Service) have demonstrated that this is possible but requires ring fencing resources at the outset, to make further investment decisions as the programme progresses.
- The evidence collected across the different phases of the study shows that pre-existing partnerships were seen as crucial to successful project implementation and attainment of results. We recommend that future iterations of the programme take this into consideration, e.g. by providing extra marks to applications that are able to demonstrate prior knowledge/experience working together and/or by sharing information on lessons learned on collaborations (in particular industry-academia) with new partnerships to speed up their process.

Robotics & AI in extreme environments as an investment area

- Our research confirmed that there are several major barriers that will continue to hamper adoption of RAI-EE even where the solutions have been proven to be cost-effective: prospective UK customers remain cautious around capital investment and there is also a wariness around the movement to these novel technologies. Client attitudes tend to be highly risk averse in all of these safety critical areas: offshore, nuclear and space, for understandable reasons. Future programmes may consider funding follow on activities that bring researchers and innovators closer to regulators and end-users via for instance regulatory sandboxes and demonstration in real world conditions.
- There is also a potential risk associated with the scalability of the solutions and the extent to which they can reach beyond a discrete number of end-users and thereby constitute a global market of sufficient scale to drive growth in the UK RAI-EE sector overall (of providers of systems and solutions). As a case in point, the strongest commercial success has been found so far in areas of application outside extreme environments. Future programmes may consider expanding their initial research into the size of the commercial opportunity of specific sectors or areas of application.

Monitoring and Evaluation

- Programmes supporting Research Hubs should consider requiring these Hubs to catalogue a list of projects/technologies to inform the understanding of their achievements of producing 'project level' indicators (including those related to progress on technology readiness level and on potential uses and commercial opportunities), similarly to what we were able to do for the CR&D and Demonstrator projects.
- More generally, we also suggest gathering additional intelligence about the projects'/participants' next steps after the completion of their grants, via the project completion forms.
- We suggest UKRI take note that there are trade-offs in the timing of the final evaluation. The more time that passes the higher the degree of attrition for primary data collection (as people move between roles, jobs and/or organisations), but the higher the probability to detect medium to long term outcomes. Our recommendation is that the final phase does not take place more than 6 months after the projects end, particularly if there is not follow on funding.
- We also recommend that multi-phased evaluations include a Process Evaluation in the first and last phase of the studies (and that this is resourced accordingly) to update the knowledge and understanding of the extent to which the process (specifically programme design and delivery) supported the attainment of expected outcomes.



Main report

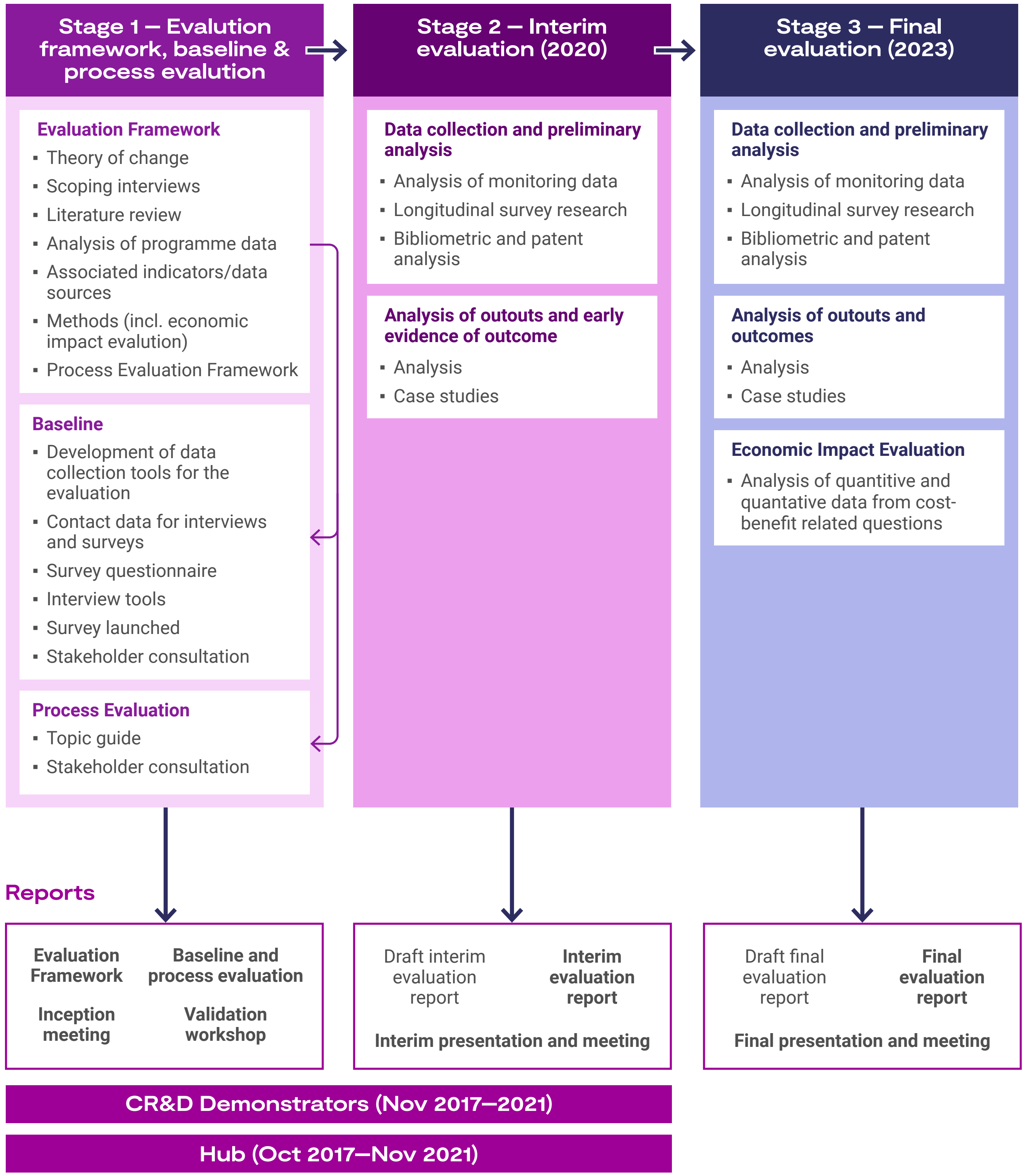
1 — Introduction

1.1 — This report

This report presents the Final Evaluation of the Industrial Strategy Challenge Fund in Robotics and Artificial Intelligence in Extreme Environments (ISCF RAI-EE). It has been prepared by Technopolis and Ipsos MORI, with contributions from Clarivate.

The evaluation was conducted over three stages as shown in **Figure 1** and it has included a Baseline and Process Evaluation (delivered in 2019), the Interim Evaluation (delivered in 2020) and Final evaluation (this report). The figure also shows how the different stages of the evaluation aligns with the programme activities. This report brings together all the evidence collected over the three phases and can be read as a standalone document.

Figure 1 – Overall approach to the evaluation



1.2 — The objectives of the evaluation

The main objectives of the overall evaluation are:

- To assess how far the ISCF RAI-EE is making an impact against its original aims.
- To test the extent to which the programme will deliver the outcomes and impact of the ISCF RAI delivery plan and the extent to which these are attributable to ISCF funding.
- Consider whether there are interim outcomes that provide an indication of future impact.

Additionally, the evaluation also examined how the ISCF RAI-EE programme was being delivered, with a particular focus on whether improvements could be made to existing processes. This analysis was included in the 2019 Process evaluation.

1.3 — Methodology, caveats, and limitations

The full methodology used in the Interim evaluation is explained in the Evaluation Framework Report (August 2018), presented as a separate document. This section presents a brief summary of the main strands of work.

The Final evaluation has been conducted using a mixed-methods approach, including:

Analysis of secondary data sources

We have analysed the portfolio of projects funded under the programme and its current status using monitoring reports; extracted and analysed information from ResearchFish on outcomes emerging from the Research Hubs; and linked data on successful and unsuccessful applicants with Bloomberg and Pitchbook to collect information on equity investment attracted by participant companies and compare it against it a control group.

Longitudinal surveys

We conducted a final wave of the longitudinal survey between December 2022 and February 2023. Previous waves took place in November–December 2018 (baseline) and November 2019–January 2020 (interim). The sample for the survey was firms that applied for funding through Hubs, Innovation R&D and Demonstrator projects; we included both successful and unsuccessful applicants and both EE and non-EE projects.

Unlike previous waves of the survey, the survey focused only on businesses. We did not include academic researchers, nor organisations that are end-users of the technology but did not apply to the fund, because of previously low response rates from these groups.

The survey was conducted by telephone and the questionnaire took around 28 minutes to complete. Telephone surveys are our preferred method to contact businesses and professionals – online surveys generally have a lower response rate than telephone surveys (because they are easier to ignore and to abandon midway).

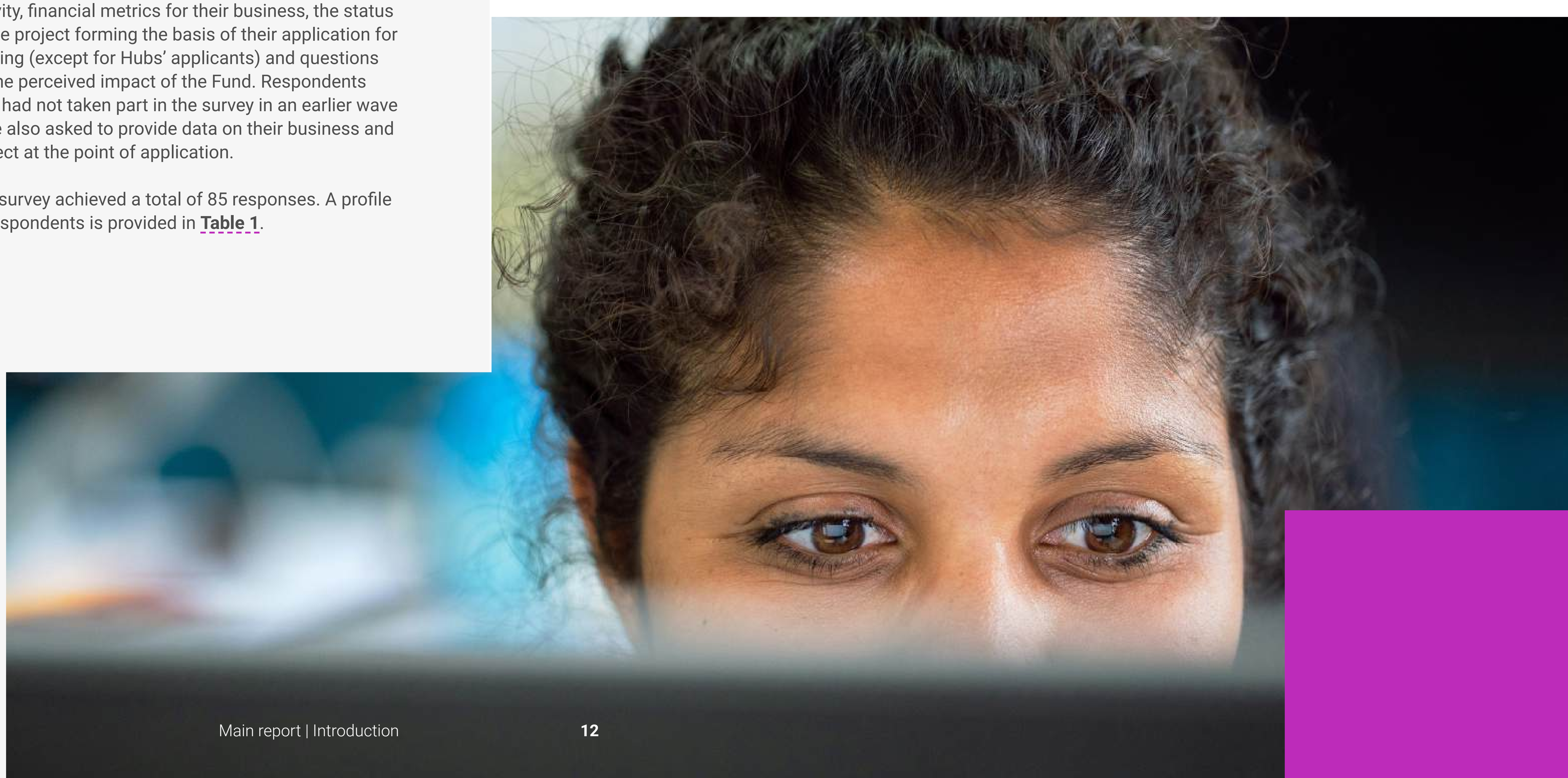
Respondents were asked about their business' R&D activity, financial metrics for their business, the status of the project forming the basis of their application for funding (except for Hubs' applicants) and questions on the perceived impact of the Fund. Respondents who had not taken part in the survey in an earlier wave were also asked to provide data on their business and project at the point of application.

The survey achieved a total of 85 responses. A profile of respondents is provided in Table 1.

Table 1 – Longitudinal survey – response rates

*Source: Longitudinal Survey (IPSOS) *.Response rates from Hubs are relatively low but they reflect the fact that we have aimed at addressing a large pool of researchers and companies involved In the Hubs, some of whom are not heavily involved.*

Category	Number of responses	Response rate
Successful applicants	**50**	**0.17%**
Collaborative R&D and Demonstrators	43	14%
Hubs	7	11%
Unsuccessful applicants	**35**	**9%**
Collaborative R&D and Demonstrators	28	9%
Hubs	7	9%



Please note that response rates were lower than hoped for the following reasons:

1. The contact information we had for applicants was out of date (25% of the extreme environments sample no longer had a working telephone number). Where possible we sought to find more up-to-date contact details by conducting online searches.
2. The individual named in the sample was no longer in post, and no-one else at their organisation felt able to discuss the project; or the individual was in post but reported little recall of the project or application (for some projects the survey was taking place over 5 years after they had made their application). Although interviewers stressed that many of the survey questions did not relate to the application specifically, lack of involvement with or recall of the challenge fund still often resulted in reluctance to take part in the survey.
3. Applicants did not answer: on average these applicants had been called four times at different times of the day and different days of the week.

We have used three different approaches in presenting the survey data across waves to compare and contrast responses.

- **Longitudinal analysis** includes only respondents for whom we have data from all three waves of the survey. These provides the highest comparability across waves but also the lowest number responses.
- **Cross-sectional analysis** presents data based on all responses received at each time point. This provides the lowest comparability across waves but the highest number responses.
- **Mixed analysis** presents longitudinal data for baseline and interim time points plus all the data collected in the final survey. This allows boosting the number of responses available in the analysis while keeping a degree of comparability (mostly between baseline and interim stage, which in turn gives a sense of the initial trajectory of change).

In the first two, some of the baseline data was collected retrospectively at interim or final stage from respondents who did not complete the baseline survey in 2018. In mixed analysis, only baseline data collected in the baseline or interim survey is used. These approaches use different volumes of data. For example, on the survey question regarding R&D spending on RAI in EE, the longitudinal analysis uses data from 17 respondents, the cross-sectional approach uses data from 239 respondents and the mixed approach uses data from 154 respondents. Numbers may vary across different questions due to some questions being inapplicable to some respondents and "don't know" responses.

Stakeholder Interviews

10 interviews were conducted with programme delivery organisations and wider stakeholders in this final phase (in addition to 9 in the baseline and 8 in the interim stage). Interviews focussed on gathering wider market intelligence of the sectors of interest and collecting qualitative evidence of the outcomes and impacts of the programme. Wider stakeholder interviewees were selected based on their ability to provide a high-level view of particular sectors. Given the involvement of many key wider stakeholders within the research Hubs, preference was given to contacting these stakeholders for development of case studies. Appendix E presents the full list of interviewees.

Case studies

Twenty case studies have been developed: four of the research Hubs (one for each), and 16 of projects emerging from the CR&D and Demonstrator strands. This total includes a 12 that are longitudinal and have been updated at each phase of the evaluation. In contrast, 8 were added during the Final Evaluation to identify broader impacts. Each case study has been developed using a combination of desk research, analysis of project monitoring data and interviews. The case studies provide some colour and narrative to the outcomes and impacts emerging from the programme. Summaries of the case studies are presented throughout the report and fuller versions are presented in Appendix C. ISCF Robotics and Artificial Intelligence in Extreme Environments 10

Bibliometric analysis

We have updated the bibliometric analysis presented in the baseline report in order to conduct an additional validation test and present progress so far. The main outcomes are presented in the main report, while the full methodology and further analysis is presented in Appendix D.

2 — The programme

As part of a multi-billion pound Industrial Strategy Challenge Fund (ISCF), in 2017 the UK government invested around £112.3m in Robotics and Artificial Intelligence in Extreme Environments (ISCF RAI-EE).

2.1 — The strands

As stated in the Process Evaluation, the programme responded to the UK's strategic ambition of strengthening its position in a growing global market (Robotics & AI) targeting emerging sectors where the UK has particular 'natural' assets and industry capabilities (extreme environments).

As such, the initial goal of the programme was to develop novel robotics and artificial intelligence (RAI) technologies and systems that will greatly reduce the numbers of people involved directly in infrastructure inspection, maintenance, and repair in extreme environments.

£49.7m In-cash

£30.2m In-kind contributions

£9.5m From other public sector funds

£79.9m Matching funds leveraged in six years

The ultimate ambition is to make unmanned operation the standard approach in areas such as offshore energy, nuclear energy, mining, and space. Across all of these challenge areas, success would see UK-based businesses selling RAI technologies and systems around the world.

Over the six years of its existence, the programme has leveraged around £79.9m in matching funds including £49.7m in-cash and £30.2m in-kind contributions mainly from businesses involved in the programme, and £9.5m from other public sector funds. The ISCF employed a directed approach to supporting collaborative research and development, bringing together the research base and innovative businesses across the value chain. To this end, the programme had three main funding streams (or 'strands') implemented by the EPSRC and Innovate UK (now both part of UK Research and Innovation):

- Four **Use-inspired Research Hubs** running over 4 years, to drive forward and enable the commercialisation of fundamental science in RAI systems. The Hubs were university-led, with co-investment from industrial partners, and included:
  - Future AI and Robotics Hub for Space (FAIR-SPACE).
  - Offshore Robotics for the Certification of Assets (ORCA).
  - Robotics and AI in Nuclear Research Hub (RAIN).
  - National Centre for Nuclear Robotics (NCNR).[1]

- **A Collaborative R&D programme** also with co-investment from industry to accelerate the deployment of early- to mid-level TRL RAI technologies in industrial settings.
- A technology **Demonstrator programme** meant to enable businesses to test RAI systems in facilities across the UK and drive commercial readiness, with co-investment from these businesses.

At the programme inception, and in line with the ambitions of the ISCF more generally, a degree of cross-fertilisation across strands was expected, however, all three strands were launched at the same time, with most resources allocated in the first year, which have limited the degree of coordination. Challenge area expansion and COVID-19

At the onset of COVID-19 in early 2020 it became apparent that RAI technologies are needed for economic and societal resilience in several additional sectors, such as construction and healthcare. So, in line with the Government's response to the 2019 House of Commons BEIS Select Committee report on 'Automation and the future of work' and the launch of the Robotics Growth Partnership, the challenge areas were expanded to the wider Service Robotics field.[2]

In addition to the expansion of the challenge areas, the programme was also extended to accommodate disruptions to supply chains, facilities and ways of working caused by COVID-19 and subsequent lockdowns. Extensions were granted by application only, allowing those projects that were highly promising to continue with testing and to finalise their technology demonstrations.

In total, additional funds to the value of £9.5m were awarded by ISCF RAI-EE as part of either a COVID Grant, or a 1-year Extension. The additional funds served to preserve as much as possible the programme's impact in the face of COVID-19.

2.2 — The Theory of change

The ISCF RAI-EE programme was one the ISCF challenges announced in the spring of 2017. The main aims of the programme were to[3]:

- Develop robotic solutions to make a safer working environment in industries such as offshore energy, nuclear energy, space and deep mining.
- Open up new cross-disciplinary opportunities, enabling the UK to lead the development and commercialisation of RAI technologies.
- Increase productivity in these and other sectors of the UK economy through increased deployment of RAI technologies.

Taking into account the needs and challenges that sustain the rationale for intervention and overarching objectives of the programme and the ISCF overall, we developed a Theory of Change for the programme, which is briefly summarised here[4], highlighting the key short and long-term outcomes, as well as impacts that were expected from the programme. The programme aimed at achieving the following outcomes:

- Support **greater connectivity between fundamental research and industrial users**.
- Increased volume of **excellent research** in RAI for extreme environments.
- Increased **R&D investment** made in the UK in the identified challenge areas.
- Increased **inward investment and FDI** in RAI for extreme environments in the UK.
- All of the above outcomes would contribute to the **widening of UK's R&D capability and capacity in RAI for extreme and challenging environments**.

[1] The portfolio selection was assessed in the Process Evaluation report (2019). In this report we did not made an evaluative assesstment of the extent to which two Nuclear Hubs should have been selected but we do note that selection followed UKRI (and the EPSRC) standard procedures (of quality proposals), and that the programme had to move at speed to allocate resources. These two factors may have played a role in having to fund two Nuclear Hubs, and area in which the UK have strong research capabilities and research networks

[2] Robotics for a Safer World Challenge Extension Business Case

[3] See Delivery Plan, Op. Cit. p.1

[4] The full discussion on the Theory of Change is presented in the Evaluation Framework (2018)

- The programme, ultimately, aimed at supporting the **development of market ready RAI solutions for extreme environments, which in turn would lead to an increase of take-up/adoption of technologies by companies in challenge areas**.
- The **adoption of the RAI solutions** could then lead **to improved business performance**, for both the technology developers and system integrators (in the RAI sector) and for the end-users (in the challenge areas).
- It was also expected that the solutions developed under the programme would lead to **cross-sector knowledge spill-overs** including for instance power management.

Finally, the adoption of the RAI solutions was also expected to lead to **societal impacts** including reduced human exposure to hazardous environments, safer nuclear decommissioning and maintenance, and cleaner energy. This is presented in a schematic way using a Logic Model as shown in **Figure 2** below. The objectives and expected outcomes are also aligned with the overarching objectives of the ISCF to accelerate commercialisation of key technologies, and the following high-level objectives were defined for the programme[5]:

- Increased UK businesses' investment in R&D and improved R&D capability and capacity.
- Increased multi- and interdisciplinary research around the challenge areas.
- Increased business-academic engagement on innovation activities relating to the challenge areas.
- Increased collaboration between younger, smaller companies and larger, more established companies up the value chain.
- Increased overseas investment in R&D in the UK.

Challenge area expansion and COVID-19

In comparison to the original Theory of Change, routes to impact for the programme expansion and additional funding remain fundamentally the same. Programme input was unchanged aside from the extra ISCF and external funding, while the societal challenges addressed, expected long-term outcomes and wider impacts were broadened to include additional challenge areas. RAI for human safety continued to be a central theme, with the subsequent inclusion of RAI for workforce and asset resilience.

[5] ISCF Business Case (p. 17) and 'Delivery Plan for ISCF Robotics and Artificial Intelligence for Extreme and Challenging (Hazardous) Environments', p. 2

Figure 2 – Logic model – ISCF RAI in extreme environments

Source: ISCF RAI-EE Evaluation Framework (2018). Technopolis and Ipsos.

Needs/Challenges/Issues

- Unsafe working environment in traditional and emerging industrial sectors with potential growth (offshore and nuclear energy, space, deep mining).
- Societal need to mitigate the negative effects of nuclear energy (decommissioning).
- Need to increase the size and critical mass of associated industrial sectors, and to improve their economic output and productivity.
- Need to take advantage of existing capabilities and public investment in research activity in the sector.

Input/Strands/Activities

Programme management:

Foster collaborative links and synergies across the programme strands

Funding for industry-inspired research hubs (£45.4m):

Provide a leadership role in national networks.

Draw on the needs and challenges of industry to articulate a multidisciplinary research roadmap, building on underlying research capabilities of academic partners.

Develop the paths for the development of systems and solutions (use-cases, standards, integration, scale up).

Innovation programme (£35m):

Provide funding for collaborative R&D.

Organise innovation labs to foster rapid development of solutions and cross fertilisation of ideas.

Organise international innovation and trade missions (e.g. US mission).

Ad-hoc activities (e.g. NESTA, DSTL special competitions).

Demonstrator programme (£16m):

Fund feasibility studies and broker access to demonstrator facilities.

SBRI competition in key areas.

Ad-hoc activities, as the need arises.

Outputs

- Establishment of networking events, conferences.
- Industry-inspired research hubs established
- Right target groups involved (incl. companies new to RAI and to UKRI).
- Projects completed
- Researchers and trainees involved in RAI activities.
- Secondments to/from each project partner.
- New partnerships and collaborations.
- Collaborations between different types of partners (e.g. academia and businesses).
- Selection and implementation of innovation projects and activities
- Selection and implementation of demonstration projects. Use of testing facilities.

Short-term Outcomes

- Enhanced capability from new or improved skills and training.
- Increased transfer of people and knowledge between academia and industry.
- Increased absorptive capacity
- New knowledge (including multi-disciplinary research).
- Private sector leveraged funding in R&D.
- Increased RAI IP activity (incl. licensing and start-ups).
- Development of RAI solutions that can be demonstrated to end-users in real-world scenarios.

↓

- Accelerated market readiness of RAI technologies.
- Companies prepared to take up/adopt technologies.

Long-term Outcomes

- Widening of UK's R&D capability and capacity in RAI for extreme and challenging environments.
- Increased volume of excellent research in RAI for extreme environments.
- Greater connectivity between fundamental research and industrial users.
- Increased R&D investment made in the UK in identified challenges areas (off-shore and nuclear energy, space, deep mining).
- Increased inward investment and FDI in RAI for extreme environments in the UK.
- Development of market ready RAI solutions for extreme environments.
- Take-up/adoption of technologies by companies in target sectors (including new companies.
- Cross-sector knowledge spill-overs (e.g. power management).

Impact

Societal impact:

- Reduced human exposure to hazardous environments.
- Safer Nuclear decommissioning and maintenance.
- Contribution to cleaner energy.
- Skills development for global outlook.

Economic impact:

- Improved business performance (RAI).
- Improved business performance (Challenge areas).
- UK leading global markets in provision RAI solutions for extreme environments.

3 — Main findings

The section presents the main findings emerging from the Final Evaluation, with focus on the are key areas of outcome and impacts identified in the Theory of Change.

We first start with a brief summary the portfolio of projects supported by the programme and its final status to provide context to the reader and inform sub-sequent sub-sections on main findings.

3.1 — Activities

3.1.1 — Portfolio overview

The ISCF RAI-EE portfolio initially comprised **four Use-inspired Research Hubs** (as well as extension calls for the RAIN and ORCA Hubs, respectively) and **78 innovation projects** across the two strands: Innovation R&D, and Demonstrator programme (with each Hub undertaking a series of work packages and activities within the context of its own grant).

Subsequent grants were created in 2021 to compensate for delays caused by COVID-19 and maintain programme value, as well as to expand the range of R&D projects to the wider field of Service Robotics. Projects awarded from these grants were broadly classified as COVID Grants and 1-year Extension Funds. A further 66 projects were awarded under the programme extension: 16 projects under the COVID Grants and 51 projects awarded under the 1-year Extension.

The ISCF RAI-EE programme committed a total of £112.4m to Use-inspired Research Hubs, Collaborative R&D projects, Technology Demonstrators, COVID grants and to programme expansion projects. **Extra contributions to the value of £87.5m were also attracted, for a total programme investment of circa £200m**. This total investment commitment includes other public sector funding, as well as financial and non-cash contributions from non-public organisations (mostly industrial partners of the Hubs). See Table 2 for a breakdown of programme funds.

The Hubs accounted for 51% of the overall investment in the programme (£102.4m), and 44% of the ISCF RAI-EE funding (£49.3m). The average size of a Hub in total commitments was £25.6m from the RAI programme, while the average size for both Innovation R&D and Demonstrator projects was £1.05m and £1.12m respectively.

Table 2 – Number of projects and budget, per instrument
*Source: Technopolis (2023), based on client data. *Including extension calls.*

Instrument	Number of projects	Total Commitments [T=A+B+C+D] (£m)	% [A/T]	ISCF RAI Funding [A] (£m)	Other Public Sector Funding [B] (£m)	Financial Contributions [C] (£m)	Non-cash Contributions [D] (£m)	% [B+C+D/T]
Use-inspired Research Hubs	4	£102.4	51%	£49.3	£1.5	£21.5	£30.2	44%
Innovation R&D	42	£44.1	22%	£31.2	£0.3	£12.5	£0.0	28%
Demonstrator	36	£40.4	20%	£22.3	£5.7	£12.4	£0.0	20%
Sub-total	**82**	**£186.9**	**94%**	**£102.8**	**£7.5**	**£46.4**	**£30.2**	**91%**
COVID Grant	16	£0.8	0.4%	£0.8	£0.0	£0.0	£0.0	1%
1-year Ext	51	£12.1	6%	£8.8	£0.1	£3.3	£0.0	8%
Total	**149**	**£199.8**	**100%**	**£112.4**	**£7.6**	**£49.7**	**£30.2**	**100%**

With respect to the different environments, **Offshore and Nuclear are the most significant, depending on whether one looks at the portfolio in terms of project numbers or total commitments, respectively** (see Table 3). Excluding the four Hubs, which were allocated a much larger amount of resources, Nuclear is the environment with the largest average investment from the 'core' group (£777.2k), followed by Cross-cutting areas (£317.2m). Within the 'core' group, Offshore projects were the most numerous.

For the extension grants, the Healthcare and Construction environments attracted the largest average investment (£172.2k and £161.4k respectively), though it was followed closely by Infrastructure (£136.5k). Apart from the generalised COVID-19 projects (which do not necessarily correspond to COVID-19-specific environments), Offshore and Agri-tech were most numerous.

The average project duration – excluding Hubs – ranged from 6 months for General Purpose projects to 23 months for Space projects.

Table 3 – Number of projects and total investment, per environment
Source: Technopolis (2022), based on client data.

Environment	Number of projects		Total Investment		Average Total Investment per project (excluding Hubs)
	#	%	£	%	£
Core group	**82**	**55.0%**	**£186.9m**	**93.5%**	**£364.4k**
Offshore	35	23.5%	£63.1	31.6%	£268.0k
Cross-cutting	20	13.4%	£18.4	9.2%	£317.2k
Nuclear	16	10.7%	£80.7	40.4%	£777.2k
Space	8	5.4%	£22.3	11.2%	£412.7k
Mining	2	1.3%	£2.5	1.2%	£188.9k
Not classified	1	0.7%	0.0	0.0%	–
Extension Grants	**67**	**45.0%**	**£12.9m**	**6.5%**	**£108.5k**
COVID-19	16	10.7%	£0.8	0.4%	£49.1k
Agri-tech	9	6.0%	£1.9	1.0%	£107.1k
Construction	6	4.0%	£1.9	1.0%	£161.4k
Offshore	6	4.0%	£1.3	0.7%	£83.6k
Infrastructure	5	3.4%	£1.5	0.8%	£136.5k
Logistics	5	3.4%	£1.3	0.6%	£157.4k
Cross-cutting	4	2.7%	£1.1	0.6%	£78.6k
Healthcare	4	2.7%	£1.2	0.6%	£172.2k
Not classified	4	2.7%	£0.1	0.0%	£24.8k
Nuclear	2	1.3%	£0.3	0.2%	£107.8k
Teleoperation/ general purpose	2	1.3%	£0.2	0.1%	£113.8k
Total	**149**	**100%**	**£200m**	**100%**	**–**

3.1.2 — Target group and new participants

3.1.2.1 – Target groups reached

One of the key outputs expected from the programme was reaching the right target group. The core programme has managed to attract a **total of 274 unique organisations** (this figure combines ISCF RAI-EE internal data and the data collected and updated during in the process of setting up the longitudinal survey). **This includes key actors in the innovation ecosystem including academic organisations (incl. UK and international universities, Government labs and research councils) (77), businesses (169) and RTOs (28)**.

77 Key actors in the innovation ecosystem

169 Businesses

28 RTOs

274 Total of unique organisations

The ISCF RAI-EE programme also includes a range of actors across the entire supply chain it intends to address. Supply chains can be very complex and are seldom confined within the same country. For the purpose of this study, we have followed a practical approach trying to assess the position of each participant with respect to a (schematic) continuum between technology developers and end-users.

Table 4 shows that the core programme has involved actors across the supply chain. The composition is broadly leans towards successful applicants towards the end of the evaluation.

Table 4 – Supply chain

Source: Technopolis (2022), based on data compiled by the study team the ISCF-RAI interim evaluation.

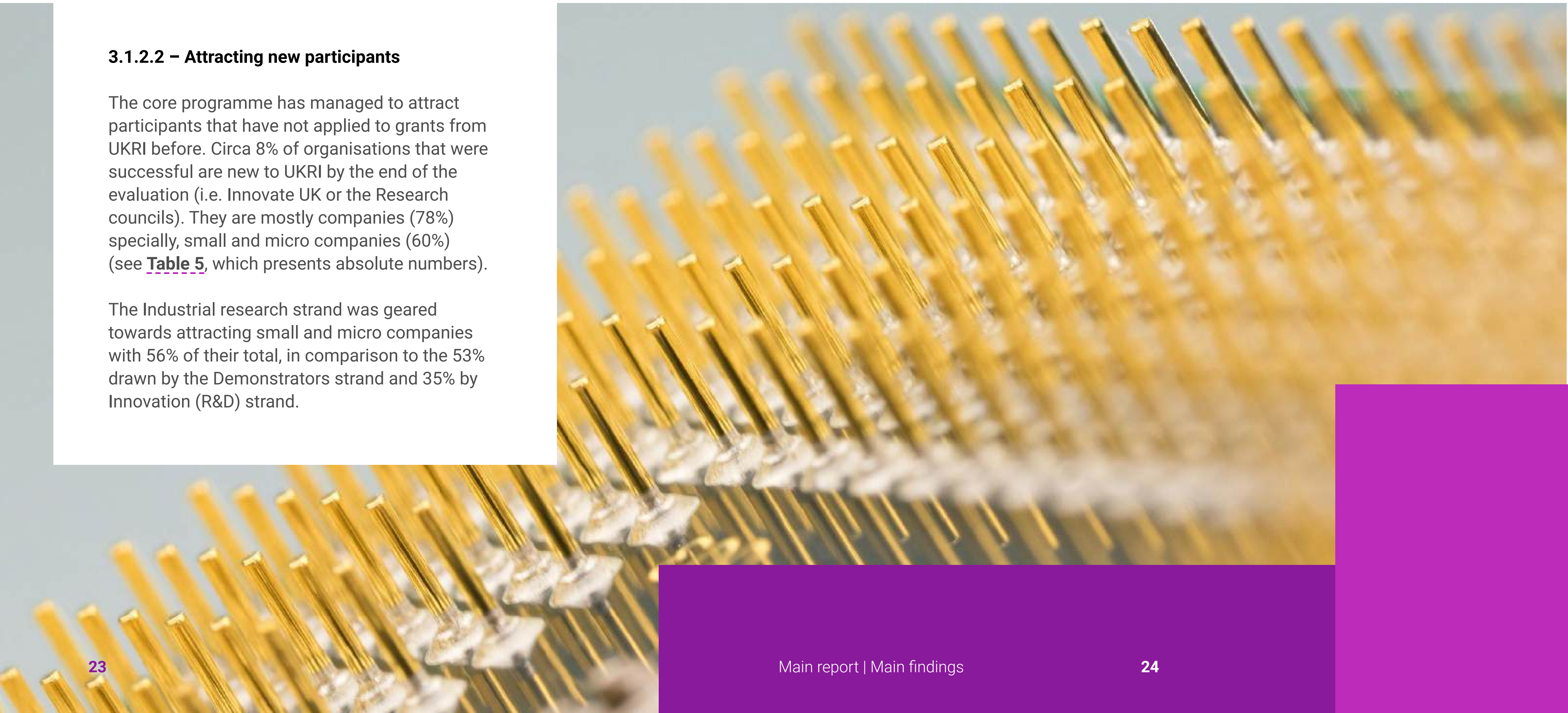
Type	Successful applicants	Grand Total
Component/technology providers	141 (51%)	147 (49%)
System integrators	39 (14%)	43 (14%)
Intermediate company	49 (18%)	57 (19%)
Public/private end-user	16 (6%)	17 (6%)
Other*	29 (11%)	37 (12%)
Total	**274 (100.0%)**	**301 (100.0%)**

**Others include organisations such as public or private foundations, 'arm's-length' public or semi-public organisations, Government agencies, organisations raising or investing funds, and sectoral organisations*

Table 5 – Successful applicants, per type of organisation and prior experience with UKRI

Source: Technopolis based on Project Master data. Information on size of the companies was provided in the Project Master data. When inconsistencies were found (e.g. the same organisation classified in different ways) we have used information Companies House data to amend the classification. In those instances, the classification was based on the EU definition (Small and micro: < 50 staff count & ≤ € 10 m turnover, Medium: < 250 staff count & ≤ € 50m turnover).

Type of organisation	New to UKRI	Not New to UKRI	Total
Academic, research councils and research centres	3	73	76
RTO, technology centres, government labs, charities	2	26	28
Large companies	3	33	36
Medium companies	1	19	20
Small and micro companies	14	99	113
Total	**23**	**251**	**274**



3.1.2.2 – Attracting new participants

The core programme has managed to attract participants that have not applied to grants from UKRI before. Circa 8% of organisations that were successful are new to UKRI by the end of the evaluation (i.e. Innovate UK or the Research councils). They are mostly companies (78%) specially, small and micro companies (60%) (see Table 5, which presents absolute numbers).

The Industrial research strand was geared towards attracting small and micro companies with 56% of their total, in comparison to the 53% drawn by the Demonstrators strand and 35% by Innovation (R&D) strand.

In terms of their position in the supply chain, successful applicants that are new to UKRI towards the end of the evaluation are component/ technology providers or system integrators (5%), Intermediate companies (6%) and Public/private end use (6%) (see Table 6 which presents the information in absolute numbers).

Table 6 – Successful applicants, per position across the supply chain and prior experience with UKRI
Source: Technopolis based on Project Master data.

Supply chain	New to UKRI	Not New to UKRI	Total
Component/ technology providers	7	134	141
System integrators	0	39	39
Intermediate company	3	46	49
Public/private end user	1	15	16
Other	12	17	29
Total	**23**	**251**	**274**

3.2 — Outputs and outcomes — with focus on RAI in Extreme Environments

This section presents progress with respect to short and long-term outcomes set out in Theory of Change. When possible, we have gathered data on both successful and unsuccessful applicants in order to:

- Estimate the outcomes attained by programme participants.
- Subsequently make a comparison with a counterfactual scenario (provided by control group of unsuccessful applicants) to assess the (net) effect of the programme.

3.2.1 — Counterfactual (self-assessment)

Evidence collected via survey suggests that there is a medium to high level of additionality of ISCF-RAI EE in terms of access to funding.

We asked project participants to reflect on what would have happened to their projects in the absence of the support provided by the programme. The question focuses on projects, so it was only collected for CR&D and Demonstrator applicants.

Around **half of applicants said their project would not have happened without ISCF-RAI EE funding**. Over the three waves of the survey, 167 CR&D and Demonstrator applicants for projects in extreme environments and 38 applicants for projects in other areas were asked whether they took their project forward in any form after their application was declined, or (for successful applicants) if they would have done so had their application been declined. Just over half of applicants (51%) said the project did not/ would not have gone ahead without funding.

When looking only at successful applicants, 53% claimed that their project would not have been taken forward in any form without the ISCF-RAI funding. These percentages are the same whether the non-EE projects are included or excluded.

The 59% of unsuccessful applicants whose extreme environments projects went ahead without ISCF-RAI funding reported that this meant the project took place over a longer timescale (65% of projects) and/or with reduced scope, in other words meeting fewer objectives (55%). Some projects also reported that they had gone ahead at a later date (35%), at a reduced scale of investment (35%) or in a different country (25%). Only one declined project reported that it had been affected by none of these changes.

All together these results indicate that access to the programme does allow companies to pursue their original project objectives, allowing them to move more quickly or with a more ambitious scope. This is further substantiated by our evidence on outcomes, specifically in terms of technology readiness level progression (See **Section 3.2.4**).

3.2.2 — New partnerships and collaborations

The design of the challenge, in itself, has invited the collaboration of the research community with industry. **All the Use-inspired Research Hubs have been set up to include universities and research groups as well as industrial partners including end-users** (and a contribution of 50% of the value of public funding, in cash or in kind). Each Hub has included an average more than ~7 partners including national and international universities universities/research groups, government labs and research councils and industrial partners.

The CR&D also requires the collaboration of companies with knowledge providers, while the demonstrators have also linked companies (mostly small business) and testing infrastructure (available at universities, and public institutes) that would otherwise not be available to them. CR&D projects have included more than 3 organisations on average, while the demonstrators have included more than 2 on average.

Table 7 – New partnerships and collaborations
Source: Project data.

	Number of collaborative grants	Number of non-collaborative grants	Avg. participants (all projects)
Use-inspired Research Hubs	4	0	6.8
Demonstrator	27	9	2.3
CR&D	34	8	3.6
1-year extensions	28	22	2.0
COVID-19 Grants	0	16	1.0

Finally, the programme has also facilitated the collaboration of smaller companies and larger, more established companies up the value chain, in line with the ISCF overarching objective. **Figure 3** shows that all of the Use-inspired Research Hubs include industrial partners from different sizes, while this is the case for 52% of the projects under the CR&D strands and 22% of the Demonstrator strand. On the latter, this is line with the configuration of the strand which is geared mostly towards attracting micro companies which do to not have access to testing facilities. However, even in this case, collaboration across the supply chain has been facilitated by the programme.

The extension grants also supported projects that facilitated the collaboration of smaller companies and larger, more established companies but to lesser degree, and only through the 1-year extension projects.

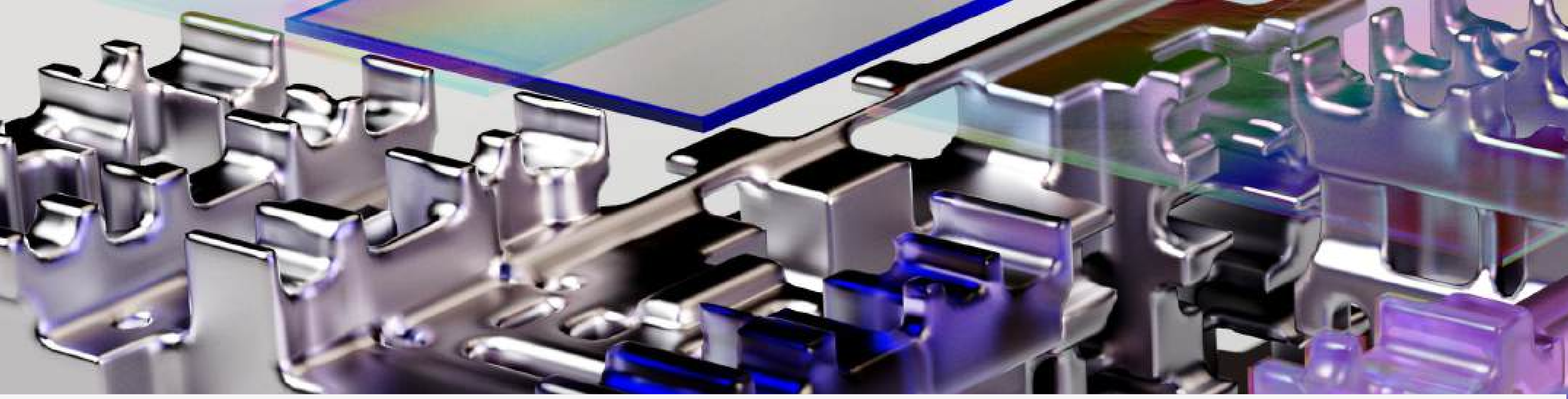
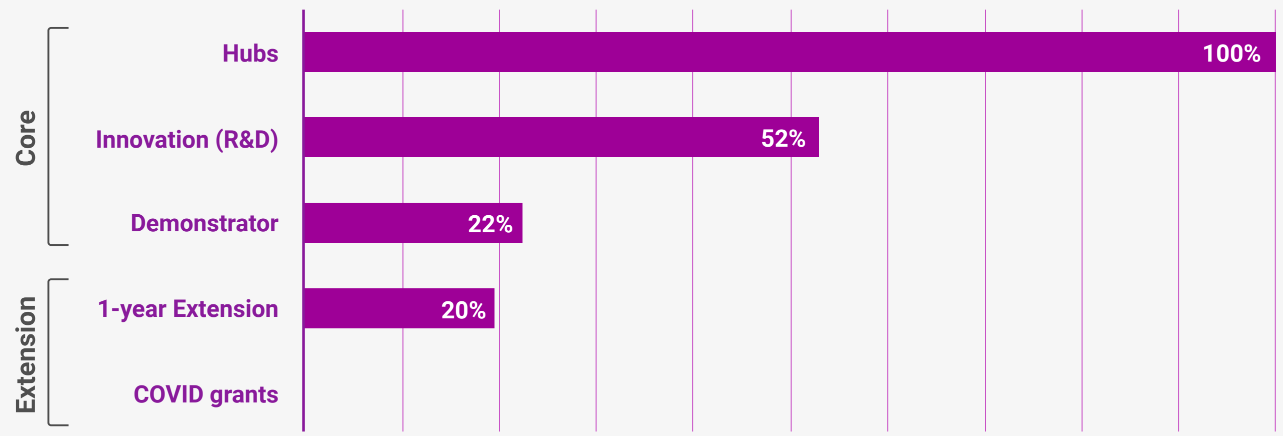


Figure 3 – Percentage of projects that include a large company and a medium or small & micro company as collaborators (lead or partner)
Source: Technopolis based on Project Master data.



In the baseline we found that the majority of successful applicants (95%) were already workingon collaborative RAI-EE projects or research grants at the point of their application, although applicant businesses were less likely to be undertaking projects with academic partners than with commercial or industrial partners.

Collaboration also took place at the point of application. The existence of those prior relationships has been in fact named as key success factor across our case studies. Pre-existing partnerships, mostly among researchers, were seen as crucial to successful project implementation and the realisation of wider benefits, as it allows project participants to hit the ground running. This is particularly important in the context of the Hubs where large-scale programme of research had to be out together in a relatively short period of time.

Having said so, the two case studies of projects funded via de Innovation Lab said that this was an effective way to meet new partners who they had not work with before.

In term of progress and further collaboration we found at the interim stage that the group of successful applicants (across all strands) had been undertaking more collaborative RAI-EE R&D projects in comparison with the baseline position, i.e. beyond the collaboration supported by the grant. This effect has been sustained over time and there is an increase in on the number of projects RAI-EE R&D projects that businesses undertake with both academic partners (0.6 increase with respect to the baseline) and with commercial/industrial partners (0.7 increase with respect to the baseline), although the later have had a slight decrease with respect to the interim position (see Table 8). As explained in Section 1.3, we did not collect data on Academics in this final round.

Furthermore, **our longitudinal survey shows that 85% of respondents (across all strands) thought that participation in the programme would result in increased collaboration with end-users**.

Table 8 – Collaboration between academia and industry (all three strands) (cohort: longitudinal)
Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023 (n=29). Ipsos/Technopolis. Successful applicants for extreme environment projects only; all strands.

	Baseline	Interim	Final
Academics: Number of RAI-EE R&D projects with an external academic partner	2.6	3.2	–
Academics: Number of RAI-EE R&D projects with a commercial/industrial partner	2.9	3.4	–
Businesses: Number of RAI-EE R&D projects with an academic partner	2.0	2.4	2.6
Businesses: Number of RAI-EE R&D projects with a commercial/industrial partner	2.6	3.5	3.3

In the case of the Use-inspired Research Hubs, ResearchFish, as well as evidence collected from case studies and other sources, provide evidence of on collaborations. According to data from ResearchFish, the four Hubs have engaged with universities, research institutions, and industry. There are a total of 168 collaborations documented across the Hubs, with more details provided below. However, around half of the documented collaborations (51%) predate the programme as they commenced in 2017 or earlier. Of the recorded collaborations, a high percentage, 41%, have not documented any outcomes or impacts. The reasons for recorded collaborations not leading to outcomes or impacts is unknown, it may be due to incomplete data entered in ResearchFish but may also reflect the lack of outcomes or impacts emerging of those collaborations as of yet.

Table 9 – Documented collaborations by Research Hub and Year
Source: ResearchFish Data – accessed on 20/03/2023. Collaborations listed are unique, each denoting a unique collaborating organisation or distinct collaborative project.

Hub	2015	2016	2017	2018	2019	2020	2021	2022	Total
Future AI and Robotics for SPACE (FAIR-Space)			34	1		2	3	1	**41**
National Centre for Nuclear Robotics (NCNR)		1	9	5	3		1		**19**
Robotics and Artificial Intelligence for Nuclear (RAIN) and RAIN+	1	1	4	5	6	4	6	1	**28**
UK Robotics and Artificial Intelligence Hub for Offshore Energy Asset Integrity Management			37	10	6	10	16	1	**80**

We have triangulated evidence from ResearchFish with information from Interim reports and via interviews and provide an assessment on how industrial engagement happened in practice and the extent to which the partnerships have remained over time.

This shows that, despite the fact that Use-inspired Research Hubs were build around the idea of funding partnerships between academia and industry, in practice, there has been limited level of industrial involvement, with the exception of the one Nuclear Hub, where there is also evidence that suggest these partnerships have been sustained.

Table 10 – Level of industry engagement within each Hub and the progression towards higher TRL and commercialisation
Source: Technopolis (2023), based on draft report, case studies and case study interviews.

Hub	Level of industry engagement
Future AI and Robotics Hub for Space (FAIR-Space)	▪ Data provided in ResearchFish indicates that there were at least 41 FAIR-Space collaborations with external partners. ▪ However, in practice Industry links have been less strong than anticipated, especially with the space sector. The degree of industry engagement in FAIR-Space projects have been limited to providing strategic advice to the Hub. Many of these collaborations ended at the conclusion of the funding period.
Offshore Robotics for the Certification of Assets (ORCA)	▪ Despite initial challenges to industry engagement, the Hub was able to establish collaborations with 24 industry partners who provided technical expertise, advice, access to facilities or equipment, or otherwise unspecified "industry collaboration". ▪ There are also ~5 cases of financial commitment and ~6 in-kind contributions to joint projects, ~6 projects in which industry are providing access to facilities or equipment (according to ResearchFish). ▪ The collaborations have enabled several industry projects including MIRIAM, a joint project with multi-national oil and gas company Total. The Hub is continuing its collaborating with Total as the work done on MIRA now feeds into Total's ongoing project called JARVIS. ▪ It is unclear which other industry collaborations in the Hub have ended or will be pursued further.
Robotics and AI in Nuclear Research Hub (RAIN)	▪ There were 28 documented collaborations between the RAIN/RAIN+ hub and external partners in the ResearchFish data. This represents a significant increase on the interim report, when only 6 such collaborations were recorded. ▪ The industry partners provided access to facilities and expertise to support demonstration of technologies. ▪ RAIN collaborated with Nuvia on the commercialisation of CARMA, however, the engagement with Nuvia has ended due to commercial conflicts. Testing is being carried out on CARMA 3.0 with a new commercial partner Ice 9. ▪ It is unclear which other industry collaborations in the Hub have ended or will be pursued further. ▪ Additionally, NUVIA partners expressed concern that a spin-out has been created by the lead University which in their view is a direct competitor to them.
National Centre for Nuclear Robotics (NCNR)	▪ NCNR is supported by partners across various stakeholder groups with a number of organisations joining the Hub since its establishment. Industry partners have provided access to end-users and operators in nuclear decommissioning, cash and in-kind contributions. ▪ Most of the 19 collaborations began in before NCNR was established according to ResearchFish, with 9 starting in 2017. Four of these collaborations were for Innovate UK funded SBRI projects that commenced at the same time as the research Hub itself. Two are for privately funded studentships as part of the Centre for Innovative Nuclear Decommissioning Engineering which opened in 2017. A further 5 collaborations involved international partner organisations, developing strategic partnerships between the Hubs and international nuclear agencies providing either student secondments or testing facilities. ▪ The partnerships built within the Hub have progressed including those with Babcock International Group, Maddox, Sellafield, Toshiba and KUKA Robotics. For example, the Hub has received additional investment from Toshiba and KUKA Robotics. Sellafield have commissioned a programme of work to deploy AI assisted robotics to deliver cutting and sorting of contaminated waste materials.

Most case studies involve an important element of knowledge exchange between academic and industry partners, although this rarely takes the form of a one-way transfer.

All four Use-inspired Research Hubs have incorporated industry and end-user engagement as part of their governance structure, such as the ORCA Industry Leadership Opportunities Panel (ILOP) and the NCNR Partnership Fund Committee. In addition, several Use-inspired Research Hubs have set up dedicated funds for innovation projects with industry, such as the NCNR's Flexible Partnership Fund and the FAIR-Space Partnership Programme. However, over the lifetime of the Hubs there appears to be diminishing returns from the structure of the investment. The early-stage nature of the research, driven by academic interests, meant that industry saw limited opportunity to incorporate Hub research into their product pipelines. Early enthusiasm for collaboration waned as it became clearer that it would be difficult to complete research within the length of the programme. While some industry partners have remained affiliated, and even continued to support the research after funding concluded (i.e. Sellafield), this has not been universal or extensive. This is further substantiated by the level of industrial investment as showcase in **Table 11**.

The box below further showcases how collaborations supported under the programme has led to further developments and benefits. It also shows that even after a successful project completion, uptake of the final solution has remained challenging, a common thread in the evaluation.

Case study 1 –
Prometheus

Source: Technopolis (2023), based on case studies.

The Prometheus collaborative R&D project aims to facilitate the inspection of voids, such as subterranean mines, which lie below the rail network. Since the mine environment is beyond-visual-line-of-sight (BVLOS) and a GPS denied environment, robotic technology which can autonomously navigate through the mine using advanced single-photon 3D imager and off-the-shelf sensors is required for such inspections. The project is still ongoing but on track to meeting its objectives.

The case shows how successful collaborations can unlock series of other benefits:

The project is led by the software company, Headlight AI, and brings together three businesses, three academic partners, and an end user, Network Rail. This consortium combines expertise in areas such as AI software, drone operations and systems, and is driven by clear, user-defined problems and needs. The collaborative nature of the project and mutual trust between the partners have accelerated its development, and collaboration between academic and industry partners within the project has proved mutually beneficial, the former providing credibility and access to the newest developments, and access to hardware and facilities respectively.

The project has already provided a number of benefits to partners. These include influencing organisational strategies, generating employment and enabling better connections between industry partners and the science base.

Ultimately, despite project success, Network Rail chose not to further pursue this research pathway. Despite that, Headlight AI felt that the funding has allowed them to better connect with the RAI science base and that the learning from this project could help develop more RAI solutions. A joint scientific paper was published by Headlight AI and the academic partners. The drone was put on display in the National Railway Museum in York on 11 January 2023 as part of its Autonomous Technology season.

3.2.3 — R&D activity and investment

This sub-section shows that participation in ISCF RAI-EE has stimulated additional investment in this area by programme participants in CR&D and Demonstrators (in exceeds of what would have happened otherwise). (Median) Cumulative funding on projects has increased by £475k between the baseline and final positions, in comparison with the unsuccessful applicants where investment has remained the same (at around £30k). However, final conclusions on R&D investment are a bit more uncertain as different results are obtained across the three cohorts of data, but the evidence suggests that the programme may have stabilised R&D spending which may have otherwise fallen heavily, in line with the decline in UK investments (2019) in robotics more generally[6], at least for a period of time.

3.2.3.1 – Cumulative funding

One of the expected outputs of the programme is to leverage extra funds to support RAI in EE related projects. Successful applicants to the CR&D and Demonstrators were asked to report the amount that their company/research group had spent on the development of the project to date, including the amount spent on the project prior to the application.

It is estimated that successful applicants had already spent circa £25k (median value) on the project at the point of applying for the grant (baseline value) and **have invested an extra £500k (median value)** since the project started (and up to Dec 22/Feb 23), representing slower but steady increase in investment at the interim and final stage. This median value is the same across all cohorts under analysis (longitudinal and cross-sectional data) (see **Appendix A**).

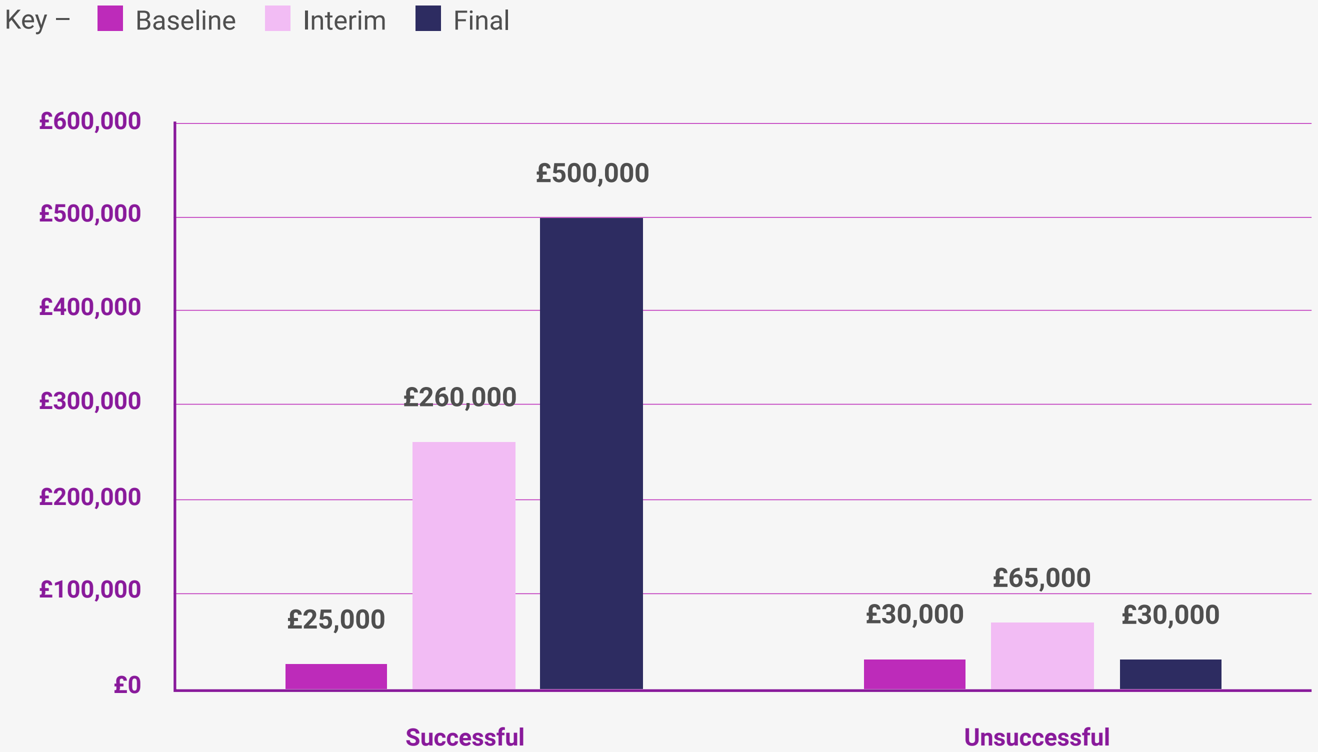
This is a substantial increase with respect to unsuccessful applicants where cumulative expenditure has remained more or less close to the baseline. These values do change when we look only at the longitudinal data (but sample is small, and results should be taken with caution) and is very similar to results from the cross-sectional data. In both cases the conclusion remains the same: **successful applicants have invested considerably more in their RAI-EE projects over time, in comparison with unsuccessful applicants** which indicates a positive result in comparison with the counterfactual scenario.

Furthermore, this cumulative spend goes beyond the value of the grant. Looking at spend in the period since the application, we find that 30 (of 33 for whom we could calculate this) had spent more than the size of their total grant. For the 33 for whom we could calculate it, successful applicants had spent £366k more (median) than the grant they received.

[6] Academics were asked about the spend of their research team on applied research into Robotics and/or Artificial Intelligence for use in extreme environments (in a given academic year). Similarly, companies were asked about their spend on applied research (also into Robotics and/or Artificial Intelligence for use in extreme environments) (in a given financial year).

Figure 4 – Cumulative project expenditure (median) (all three stands, businesses) (cohort: mixed)

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023, Ipsos/Technopolis. Base: CR&D and Demonstrator business applicants for projects in extreme environments. 60 successful and 19 unsuccessful applicants with data at both baseline and interim, plus 31 successful and 8 unsuccessful applicants from final wave. Baseline data collected from additional respondents in final wave has not been added. NB. Where a respondent could not give an exact answer and gave a band, the mid-point of that band was used. Where answer to interim question was lower than figure given at baseline these figures were added together to produce interim answer, on the assumption that respondents had not appreciated that the question was cumulative.



In the case of the Use-inspired Research Hubs, ResearchFish provides evidence of further funding being secured.

- Across the four Hubs, there are more at least 113 examples of newly secured funds, with all new funds totalling £118m. A breakdown of these funds across the Hubs can be seen adjacent in **Table 11**. This represents a marked increase since the Interim Phase in both the number of funding opportunities secured (40) and the total value of funding (£39m) since the Interim Phase. Note that 98% of these further investments correspond to public sources.
- Unlike during the interim phase, where the split between EU and UK further funding was nearly equal, we have seen UK funding for hub projects far outpace other sources. To date, the Hubs have garnered significant funding from UK sources, accounting for 79% of total further funding.
- Funding from EU sources was concentrated in a small number of agreements, with €25.4m covering only 12 projects across the four Hubs. These 12 projects, while only 10% of the overall instances of further funding accounted for 10% of further funding the Hubs have received.

Table 11 – Value of further funding secured by research Hubs, as recorded in ResearchFish
Source: ResearchFish data provided via UKRI Gateway to Research. At the time of writing of this report the latest snapshot is data 24/03/2023.

	FAIR-Space	NCNR	ORCA	RAIN	Total
Number of funding instances	24	30	28	31	113
Value of further funding	£26.2m	£29.0m	£29.1	£25.8m	£110.1m
% public source	97.5%	99.6%	97.6%	94.7%	98.1%
Funding by Country					
United Kingdom	£25.6m	£21.1m	£17.8m	£23.0m	£87.5m
European Union	€0.64m	€9.0m	€12.8	€3.0m	€25.4m
United States	$0	$8.5k	$0	$0	$8.5k

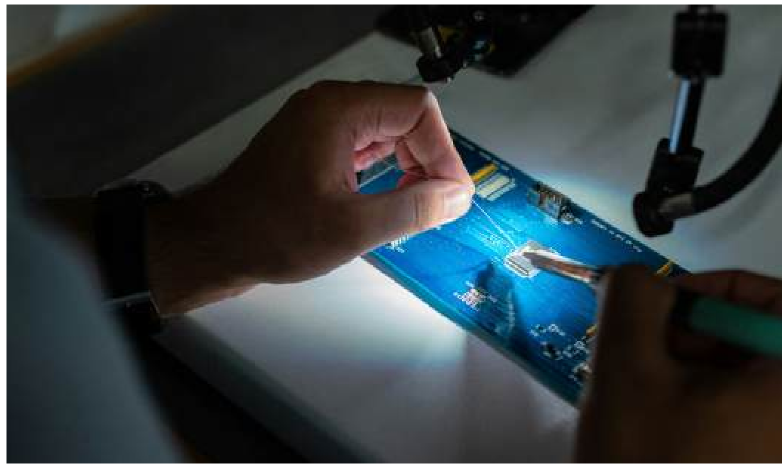
3.2.3.2 – R&D investments

Annual R&D spending on RAI in EE has remained constant between the baseline and interim stage (at around £2.66m a year on average). This includes the value of the grant (on average, £106k per year of project, based on the CR&D and demonstrator grants for which we have data at project level). There is a decline in the value of R&D investment at this final stage (to £1.48m see **Figure 5**) that may suggest that companies have decided to decrease investment in this area. One could also argue that in some cases a decision was made that further R&D investment is not needed as developments have moved to the point of maintenance and commercialisation, but evidence suggest that is not the case for the majority of projects.

Evidence of decline in R&D investment is consistent when looking at the longitudinal and cross-sectional cohorts (where declined has happened at both the interim and final stage).

Similarly, annual R&D spending on RAI in EE has declined steadily and more considerably in the group of unsuccessful applicants for the two cohorts of data for which there is sufficient information (cross-sectional and mixed).

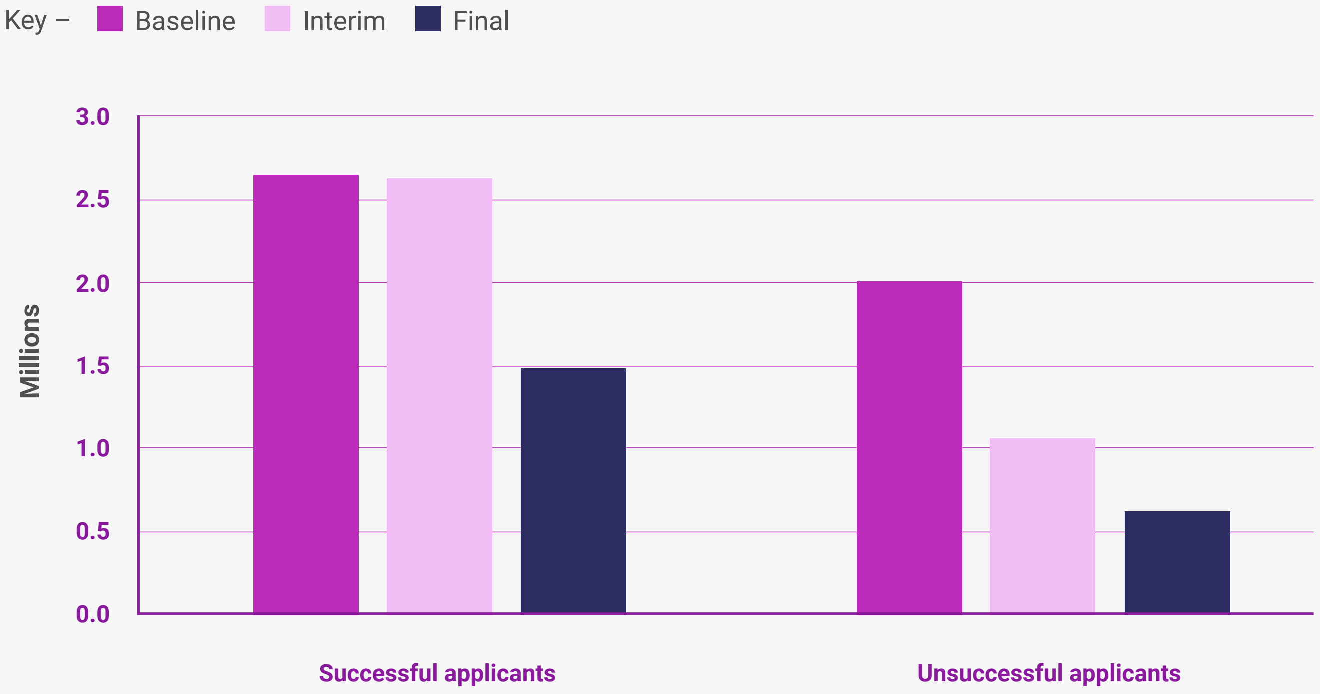
This evidence suggests that the programme may have stabilised R&D spending which may have otherwise fallen heavily, in line with the decline in UK investments (2019) in robotics more generally[7], at least for a period of time.



[7] Academics were asked about the spend of their research team on applied research into Robotics and/or Artificial Intelligence for use in extreme environments (in a given academic year). Similarly, companies were asked about their spend on applied research (also into Robotics and/or Artificial Intelligence for use in extreme environments) (in a given financial year).

Figure 5 – Average annual R&D spending on RAI in EE, £m (all three strands, both businesses and academics) (cohort: mixed)

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: Applicants for projects in extreme environments. 81 successful and 45 unsuccessful applicants with data at both baseline and interim, plus 34 successful and 13 unsuccessful applicants from final wave. Baseline data collected from additional respondents in final wave has not been added.



We further explore differences in R&D investment across strands and environment, however not much can be concluded from this data given the low number of observations. Note that the same pattern of decline of R&D investment is identified when analysing the data at this level, but again results need to be taken with caution.

Table 12 – Average annual R&D spending on RAI in EE, £m (per strand and environment) (cohort: mixed)

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: 81 successful and 45 unsuccessful applicants (all three strands, both businesses and academics) for baseline and interim data. For final data, base sizes vary and are shown in each cell. "No data" correspond to the instances in which there were no respondents working only in this environment (the vast majority selected several).

	Baseline		Interim position		Final position	
	Successful applicants	Unsuccessful applicants	Successful applicants	Unsuccessful applicants	Successful applicants	Unsuccessful applicants
Strand						
Use-inspired Research Hubs (n=67)	£5.5m	£2.6m	£4.4m	£1.4m	£1.6m (n=7)	£1.0m (n=7)
CR&D and Demonstrator (n=58)	£0.5m	£0.5m	£1.3m	£0.1m	£1.3m (n=27)	£0.05m (n=6)
Environment						
Offshore energy only (n=71)	£2.4m	£2.1m	£3.1m	£1.4m	£0.9m (n=5)	£0.09m (n=2)
Space only (n=39)	£4.3m	£2.7m	£3.7m	£1.2m	£0.5m (n=1)	No Data
Deep mining only (n=33)	£2.3m	£2.0m	£2.9m	£1.5m	No Data	No Data
Nuclear energy only (n=51)	£3.6m	£1.5m	£5.2m	£1.7m	No Data	No Data

Despite the decrease in R&D investment (in RAI in extreme environments), survey data (for mixed cohort) also shows a slight increase in R&D employment in this area for successful applicants between the interim and final stage. Longitudinal data shows the opposite trend. In both cases there is an increase in R&D employment with comparison with the baseline at this final stage (of between 6 and 8 employees on average).

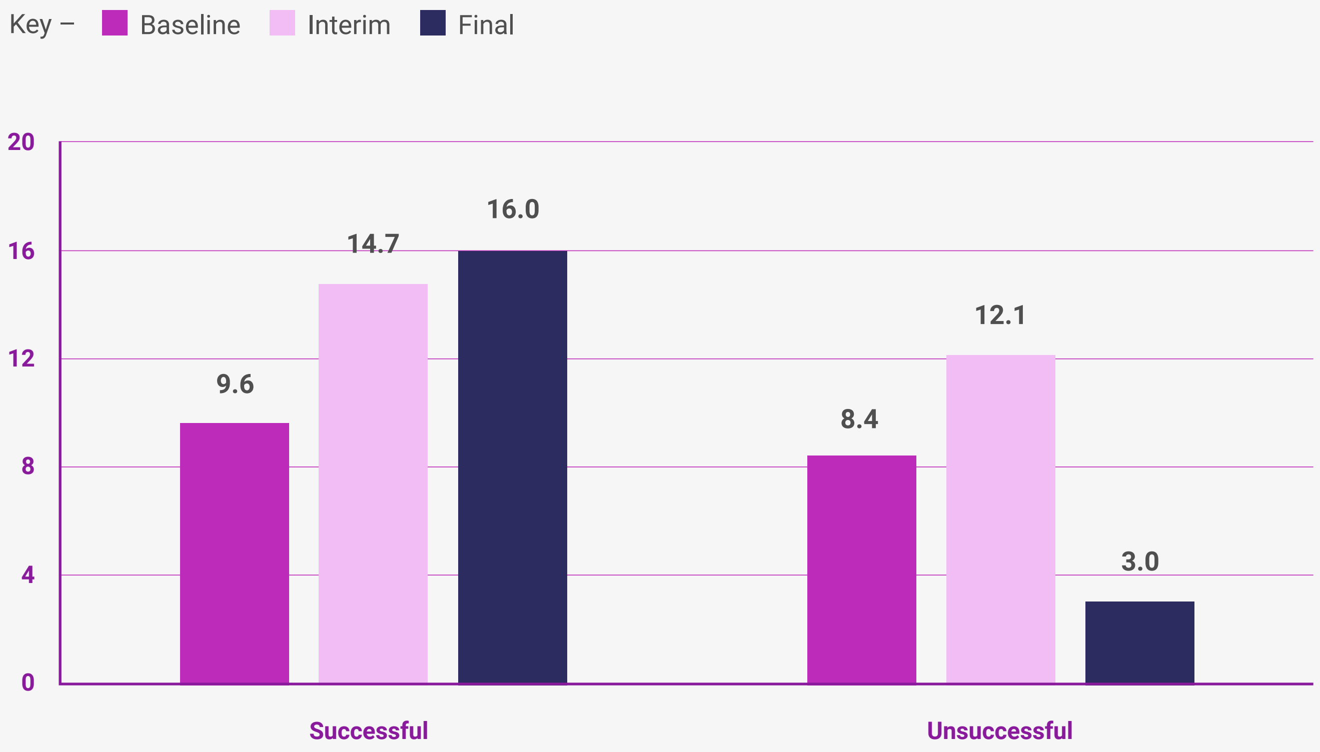
An increase in R&D employment but decrease in R&D investment may suggest a degree of extra mural activity taking place among successful applicants.

The pattern among unsuccessful applicants is clear as it reverses depending on the cohort under analysis but in both cases the level of R&D employment is substantially lower than in comparison with the successful applicants.

Taking together, this evidence suggests that the programme has stimulated R&D employment in RAI in extreme environments.

Figure 6 – Average annual R&D employment in RAI-EE, mean (all three strands, both businesses and academics) (cohort: mixed)

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: CR&D and Demonstrator business applicants for projects in extreme environments. 92 successful and 47 unsuccessful applicants with data at both baseline and interim, plus 30 successful and 13 unsuccessful applicants from final wave. Baseline data collected from additional respondents in final wave has not been added.



3.2.3.3 – Equity investment

Successful applicants have also been active in raising venture capital. Using information from Pitchbook we find that 131 successful applicants have raised equity funding since 2018, with a total value of £1,034m raised (see Table 13). This is a substantial increase with comparison with the interim position where we found that by 2020 only seven successful applicants (companies) have raised equity funding since 2018, with a total value of £98.3m.

In comparison 95 companies in the control group raised equity investment since 2018, with a total value of £85m. That equates to an average amount raised of £7.9m among successful applicants and £0.9m among unsuccessful applicants (see Table 13).

As reported before, one company (Astroscale) dominates the results, with £253m raised over three rounds since 2019. Astroscale (a Japanese space-debris removal company) opened a new in-orbit servicing facility in the UK in 2018 as part of their £4m Demonstrator grant. The company had raised £19.45m in 2017 before the programme started. In 2022, they opened a new facility in the UK to build world's first commercial space debris removal spacecraft, which has brought around 100 new jobs to Harewell.[8]

Overall, the ISCF-RAI EE programme has contributed to these positive results in terms of enabling the attraction of venture capital, but as it could be expected, it is not the only contributing factor.

[8] Astroscale opens new UK facility to build world's first commercial space debris removal spacecraft, UKSPACE, 2022

Table 13 – Equity investment raised since 2018, firms applying to Extreme Environments competitions, £m
Source: PitchBook, Ipsos UK defined user query.

Type of funding	Successful (Leads)	Successful (Collab)	Successful (Hubs)	Successful (All)	Unsuccessful
Accelerator/Incubator	1.2	0.0	0.0	1.2	0.4
Angel (individual)	2.0	0.0	0.0	2.0	0.0
Equity Crowdfunding	0.3	0.0	0.0	0.3	0.2
Seed Round	5.6	0.4	0.0	6.0	24.3
Early-Stage VC	9.8	0.0	28.3	38.0	25.0
Later Stage VC	296.4	93.4	6.1	395.9	34.9
Corporate	0.0	590.9	0.0	590.9	0.0
Total Venture Capital	**315.3**	**684.7**	**34.3**	**1,034.3**	**84.8**
Number of applicants (private sector only)	52.0	52.0	25.0	131.0	95.0
Average amount raised (£m)	**6.1**	**13.2**	**1.4**	**7.9**	**0.9**

Thinking about investment more generally (as covered in this subsection and the prior ones), the case studies revealed several ways in which the ISCF RAI-EE programme has contributed to **R&D activity and private investment** in the field.

In the first instance, the grant funding allowed the grantees to undertake more R&D in the field. The innovation case studies showed that winning ISCF RAI-EE grants from Innovate UK often allowed companies to prioritise R&D activities that had previously been a more marginal pursuit (e.g. ROVCO).

The case studies further provided examples where ISCF-RAI-EE grants have enabled companies to attract further investment for R&D. Even when additional investments are unrelated to the specific ISCF-funded project, our case studies show that the ISCF-RAI-EE grant can provide the basis for a broader technology roadmap and bring credibility in the eyes of investors. The case study of ROVCO – summarised in Case study 2 – illustrates these two routes to additional investment and R&D activity.

However, commercialisation remains a challenge, particularly in the area of autonomy due to the additional requirements for safety and reliability. Several case studies indicated a need for and the challenge of access to specialised testing facilities (ROVCO's A2I2) and real-world demonstration opportunities (UAV Logistics) prior to the possibility of commercialisation.

Case study 2 –
ROVCO

Source: Technopolis (2023), based on case studies.

With support from a series of ISCF project grants, ROVCO has developed a camera system, including software to generate 3D images, which provide a much more accurate assessment of objects under water, and the camera to support this capability. In addition, the improved vision provided by the camera system is a key prerequisite for developing autonomous underwater vehicles (AUVs) without tethers, able to navigate accurately in tight spaces close to offshore assets without causing collisions and damage. Ultimately, the technology can improve effectiveness and efficiency of offshore asset management, increasing accuracy and enabling significant savings from automated navigation and image processing, and from limiting the need to bring analysts offshore for inspections.

The ISCF RAI-EE grants have directly enabled the growth of the company in terms of staff, R&D activity and investment. ROVCO was founded in 2016 and prior to its first UKRI project started in 2017, ROVCO had a staff of two people. The first grant directly enabled the hiring of two additional staff to do R&D. By the end of the second grant (2018), the staff count had increased to 15–20 which increased to 35 during the interim phase of the evaluation. The company has continued to grow, reaching around 90 employees in mid 2023, and have even succeeded in spinning off portions of the business to draw in further investment.

The table below lists government and external private investment attracted by ROVCO. The sequence is consistent with the suggestion that ISCF funding has enabled private investment.

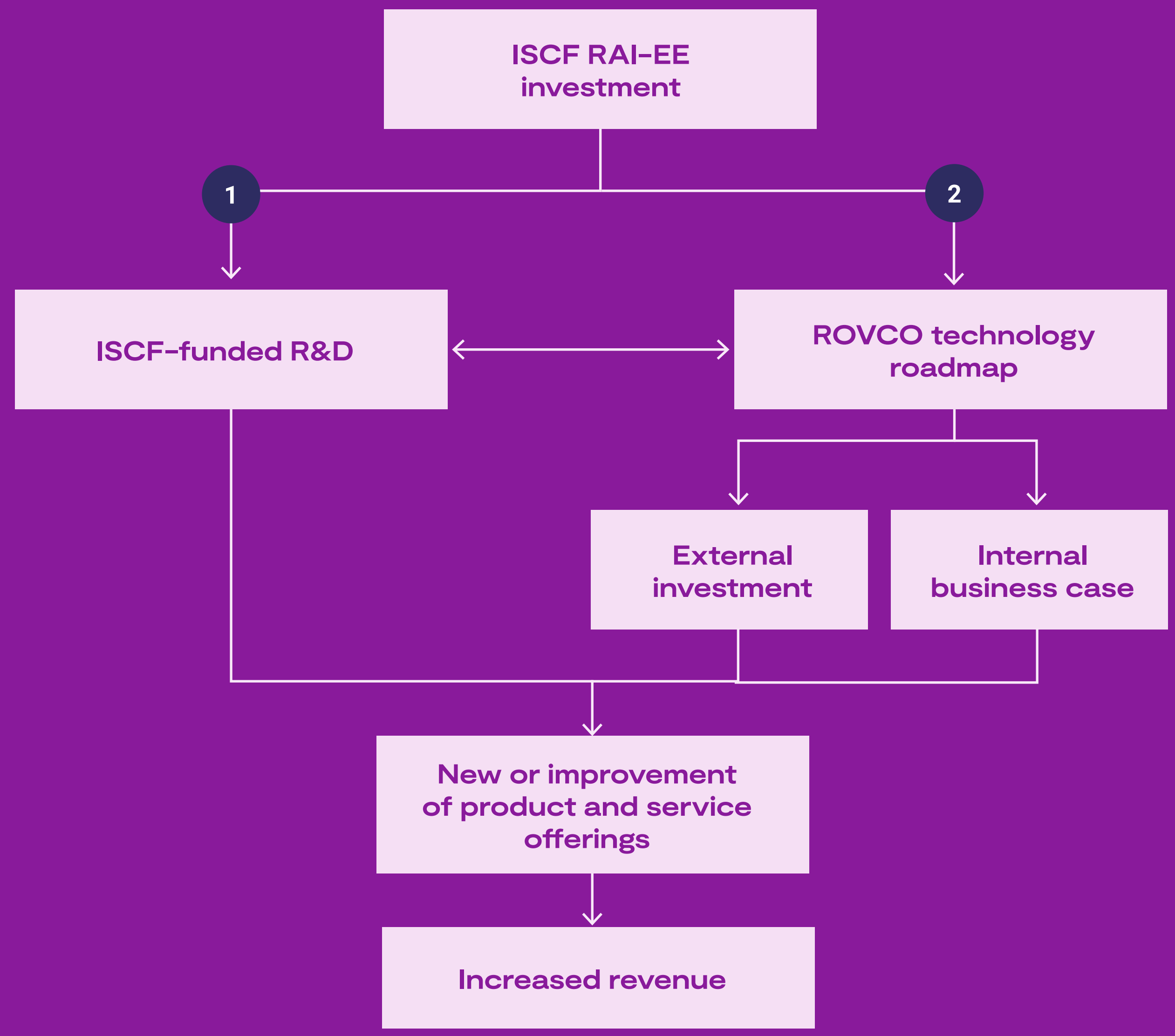
Innovate UK funding (by project start date)	Private investment
▪ March 2017: £52,396 (Feasibility). ▪ November 2017: £140,469 (Demonstrator phase 1). ▪ December 2018: £1,003,109 (Demonstrator phase 2). ▪ January 2019: £1,824,645 (Collaborative R&D).	▪ October 2017: £150,000 pre-Seed. ▪ March 2018: £1,200,000 Seed. ▪ January 2019: £1,200,000 Seed. ▪ January 2020: £5,000,000 VC (Series A). ▪ April 2022: £15,200,000 VC (Series B with Vaarst a spinout from ROVCO).

The ISCF RAI-EE programme has enabled increased investment in R&D through two interconnected routes as illustrated in the figure on the adjacent page:

Route 1 – The ISCF funded projects directly fund R&D projects which help de-risk relatively low TRL technologies.

Route 2 – The ISCF grants strengthens ROVCO's credibility and underpins the company's wider technology roadmap for the additional development and commercialisation of proven technologies. This clearly articulated route to market helps attract external investment and strengthens the internal business case for investing further in R&D.

Figure 7 – ROVCO routes to increased investment
Source: Technopolis.



3.2.4 — Technological readiness level (progress)

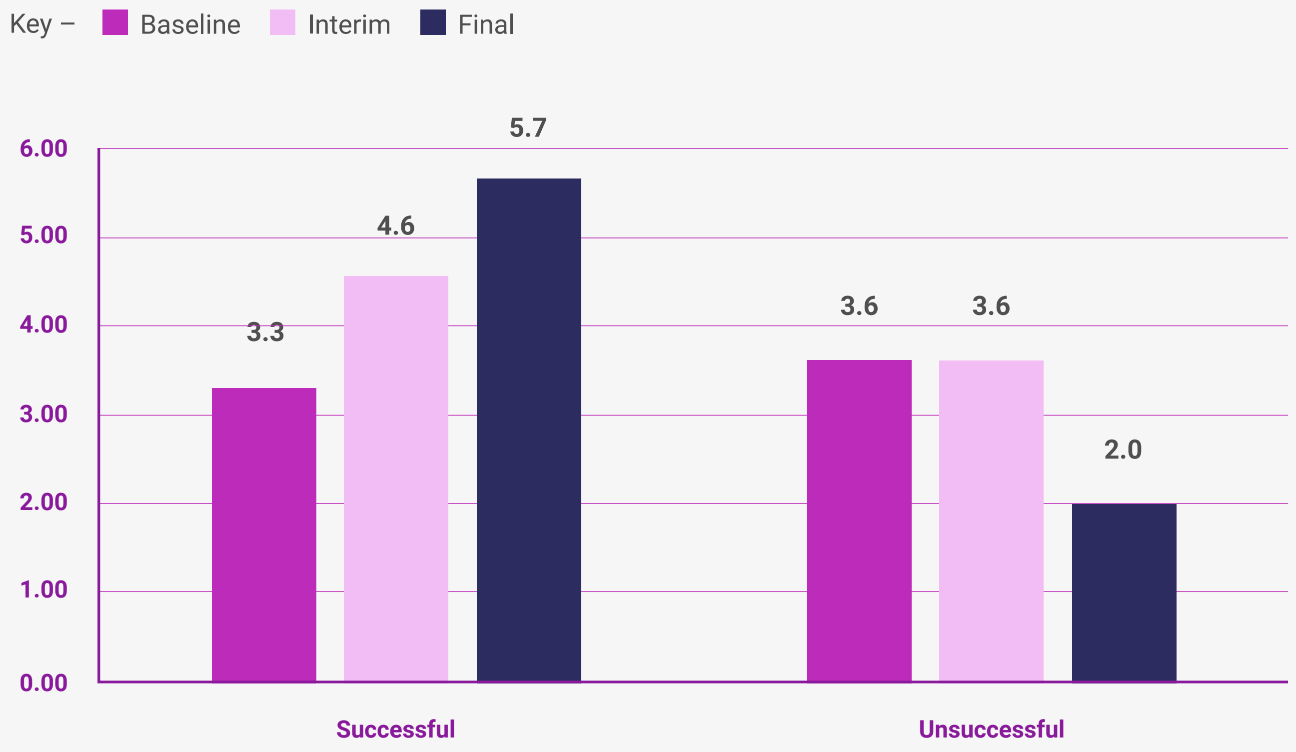
Evidence shows that funded projects in CR&D and Demonstrator strands have made some progress in terms of technological readiness level (TRL), and that progress is stronger in comparison with the counterfactual scenario. On average, funded projects appear to have progressed since the point of application by one TRL level on average, moving from specifying and developing a proof of concept to demonstrating this proof of concept in a test site (with a natural progression from the baseline through the interim and final stage as projects progressed and concluded).

Unsuccessful projects, in contrast, had remained at the same TRL level on average, whether abandoned or continuing, which provides further evidence that the programme has helped accelerating the development of RAI solutions in extreme environments, as originally intended. The decrease in value shown in the final stage correspond to the fact that this is a different sample but further emphasises low levels of maturity in the projects among that group.

Note that in this case we have no longitudinal data over three points for unsuccessful applicants, and only 7 successful ones. For these, TRL level goes from 3.4 to 4.6 to 6.1. Similar figures to ones in Figure 8 are obtained when looking at the cross-sectional cohort.

Figure 8 – Project TRL, mean (CR&D and Demonstrator strands only, both businesses and academics) (cohort: mixed)

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: 42 successful and 11 unsuccessful applicants (CR&D and Demonstrator strands only, both businesses and academics) with observations at both baseline and interim, plus 25 successful and 4 unsuccessful applicants with observations at final stage.



Given the nature of the Use-inspired Research Hubs, that are advancing a set of interconnected work packages, the study has not collected information at project level, as such we do not present a single statistic that showcases TRL progress made so far.[9]

The description of the Use-inspired Research Hubs progress (as shown in their websites, ResearchFish and the Mid-term review) shows that the overall portfolio of the Use-inspired Research Hubs is varied but mostly concentrated around applied research (instead of basic research or low TLR levels, 1–2). In fact, it seems that Use-inspired Research Hubs are predominantly focussed on TRLs 3–6, with the expectation that collaboration with industrial partners will support TRL progression from TRL5 onwards.

For example, despite NCNR's explicit priority to focus on 'fundamental low-to-medium TRLs', projects presented for the mid-term review back in includes industry collaborative projects developed to TRL7.

Table 14 provides an overview of the progress made in each Hub. The case study below further illustrates how the programme has contributed to progress at project level.

[9] The study team would like to revisit the idea of asking Use-inspired Research Hubs to catalogue a list of projects/technologies, such that we can produce indicators (e.g. TRL progress, investment) for the final evaluation.

Table 14 – Equity investment raised since 2018, firms applying to Extreme Environments competitions, £m
Source: PitchBook, Ipsos UK defined user query.

Hub	Progression towards higher TRL/Commercialisation
Future AI and Robotics Hub for Space (FAIR-Space)	FAIR-Space projects have led to the development of a ground-based robotic demonstrator that has been designed and implemented to simulate in-orbit manipulation of space targets. This demonstrator has been used by industrial organisations for development and testing. The direct contributions of the Hub in supporting TRL progression towards commercialisation for other projects are however less clear.
Offshore Robotics for the Certification of Assets (ORCA)	Industry engagement on ORCA projects enabled the development of the following technologies at varying TRLs: - Two patent applications. - The completion of more than 10 field trials. - The establishment of 1 spinout with three more in preparation.
Robotics and AI in Nuclear Research Hub (RAIN)	RAIN projects enabled the development of the following technologies at varying TRLs: - The CARMA radiation scanning autonomous robot deployed in an active area on the Sellafield site. The Hub allowed an impressive progression from TLR 4 to TRL 7 in less than two years. - RAIN projects have led to development of 4 products that are being commercialised.
National Centre for Nuclear Robotics (NCNR)	NCNR projects enabled the development of the following technologies at varying TRLs: - Advanced autonomous robotic manipulation capabilities to TRL7 inside live radioactive environments. - A mobile robotic cutting platform that has been demonstrated within test environments. Research partners are planning more demonstrations in future as the system increases TRL.

Case study 3 –

Unmanned Aerial Vehicle (UAV) based logistics capability for use in military and civilian missions

Source: Technopolis (2023), based on case studies.

The development of a UAV based logistics capability is one of several technologies being developed to address the specific of using UAVs in dangerous situations. The project demonstrates the potential for funding to rapidly advance the Technology Readiness Level of robotics initiatives.

The UAVL project began as a competition call by the MOD to develop ground-, air and sea-based logistics solutions. The challenges to be addressed were those of payload capacity, distance, and mode of delivery.

UAVL successfully met the objective capabilities with a proof-of-concept drone called the Panchito. **Over the course of the project, the team was able to successfully progress the UAV from TRL6 to TRL8**. Despite having a product nearly ready for market, its use cases remain limited remote areas. Over time, with further demonstrations and regulatory approvals, the team hopes to have a UAV that can meet any logistics need in the future.

For the full use case to be available BML have continued work on the safety and reliability

of the Panchito's autonomy via private venture funding. This additional input is required before transitioning the Panchito from a logistics prototype to a fully industrial model.

Case study 4 –

RAIN Hub and the CARMA robotic platform

Source: Technopolis (2023), based on case studies.

The Continuous Autonomous Radiation Monitoring Assistance (CARMA) is one of several technologies being developed to address the specific challenge of improving radiological monitoring of large floor areas. Developed in collaboration with Sellafield, it maps and continuously inspects floor space for radioactive contamination. It primarily aims to replace routine inspection and is not designed to be deployed in environments with high gamma-radiation. **It provides a good example of progress against Technology Readiness level**.

The development of the CARMA started in 2016 and was initially supported by a post-doctoral research award funded by the University of Manchester, Sellafield and the National Nuclear Laboratory (NNL). Thus, CARMA was not initiated by the RAIN Hub but it is now being further developed by the hub. Having undergone earlier development, it was by far the most advanced output generated from RAIN.

In the context of the hub, the University of Manchester worked closely with Sellafield to further develop the platform and were able to do so through a series of deployments at Sellafield sites. **The Hub allowed an impressive progression from TLR 4 to TRL 7 in less than two years**. Commercialisation is now being undertaken by Nuvia ltd, in collaboration with the University of Manchester with support from an Innovate UK Knowledge Transfer Partnership (KTP) grant. Ultimately, CARMA was not deployed due to commercial conflicts, but the knowledge generated has been instrumental in developing CARMA 2 and CARMA 3.0. While it does not appear that these have been made commercially available, the company continues to pursue research and development in this area.

Figure 9 – Technological development of CARMA robotic platform
Source: Technopolis.

Background:	RAIN Hub:	Commercialisation:
R&D at the University of Manchester to develop CARMA and underlying algorithms.	Further development of the CARMA platform via development at Sellafield sites.	CARMA platfrom developed for market by Nuvia, supported by Innovate UK KPT grant.

TRL4 — TRL7

3.2.5 — New knowledge

One of the key objectives of the programme, in particular the Use-inspired Research Hubs, is to support the generation of new knowledge, in particular new knowledge emerging from multidisciplinary research.

The Use-inspired Research Hubs are multi-disciplinary by design as universities participate via research groups that bring together different departments, including Electrical and Electronic Engineering, Mechanical, Aerospace and Civil Engineering and Computer Science.

Furthermore, our longitudinal survey data from the baseline and interim phases indicate that:

95%

successful academic applicants (n=55) (across all strands) expected the project to result in increased multidisciplinary research in the area of robotics and artificial intelligence, applied to extreme environments.

Analysis of ResearchFish shows that the research projects undertaken by the Use-inspired Research Hubs generate (codified) new knowledge and publications, with each hub reporting a large number of publications related to the ISCF-RAI-EE grant, and a total of 1,334 publications (including peer-reviewed articles, conference proceedings and working papers). This represents a significant rise (337%) above the 395 publications recorded during the interim phase. This represents 1,256 more publications than during the baseline research phase when only 78 publications were documented.

We conducted additional validity checks by matching the publications submitted to ResearchFish with information on Web of Sciences. The matching exercise resulted in a dataset of 722 papers (once duplicates had been removed). This means that some of the papers submitted to ResearchFish may not be peer reviewed publications.

Of the 722 matched records, 125 (17.3%) were found by our keyword search for robotics inextreme environment papers (see Appendix D). However, this figure rises to 501 (69.4%) when compared to the keyword search of all robotics papers.

This suggests that not all papers that are relevant to robotics in extreme environments contain keywords relevant to extreme environments in their title or abstract. This is to be expected as researchers do not always discuss potential applications of their work in detail in their research papers.

More interesting, we compared the scientific impact of the papers emerging from the programme and those produced by other UK based authors. We find that the average category normalised citation impact of the **722 papers was 2.32, higher than both the UK (1.42) and world averages (1.12) for Robotics in Extreme Environments research**. This indicates that the scientific output emerging from the programme has been of high calibre and scientific excellence than it is the 'norm'.

Other forms of codified knowledge have emerged from the Use-inspired Research Hubs in the form of 'Software, research materials and databases for research' including:

- The development of new, open-source computer models/algorithms for robotic path planning and simulation, and inspection algorithms.
- Contributions and improvements to existing software toolboxes (such as the CAPTAIN Toolbox and the L-CAS ROS software repository).
- Collection and provision of field trials dataset to support testing and validation of wider Hub activities.
- Integration of software with a robotics platform (e.g. 3D vision systems and VR interfaces) to provide test rig for wider Hub software research activities.

However, note that a comparison with UKRI funded grants that started in 2018–2022 show that the number of outputs per £m invested is lower for ISCF-RAI EE with the exception of publications, which further showcases the academic focus of the Hubs.

Finally, a total of 2,424 dissemination activities have been recorded in ResearchFish across all four of the Hubs. These activities include talks and presentations, panel discussions, engagements with media or press and participation in workshops.

2,424 **Total dissemination activities**

Table 15 – Outputs of the Use-inspired Research Hubs, from ResearchFish
Source: ResearchFish (2019), accessed via **UKRI Gateway to Research**.

	RAIN	FAIR-SPACE	ORCA	NCNR	Total
Publications (incl. peer-reviewed articles, conference proceedings and working papers)	408	170	362	394	1,334
Software	9	2	3	2	16
Research materials	1	0	6	3	10
Research databases & models	20	1	2	3	26
Dissemination	1,206	298	772	148	2,424

Table 16 – Outputs of the Use-inspired Research Hubs, from ResearchFish
Source: ResearchFish (2019), accessed via UKRI Gateway to Research.

	Hubs	UKRI
Publications (incl. peer-reviewed articles, conference proceedings and working papers)	25.5	15.66
Software	0.32	0.36
Research materials	0.20	0.45
Research databases & models	0.53	0.82

In terms of the **wider landscape**, the UK has maintained its position as a global player in the production of scientific knowledge in the area of RAI in extreme environments.

Since 2019, the number of publications that the UK has output (**Figure 1**) continued to increase until 2021, reaching a peak of 245 documents, after which point there was a decrease to 196. Despite this, the UK has continued to output the third largest number of documents globally, sustaining the lead over Japan it gained in 2018.

The USA and China are still leading in terms of the quantity of documents relating to RAI in extreme environments by a significant margin, although there has been exponential increase for China particularly. Between 2019 and 2022, China has seen a 41% increase in outputs, compared to the USA which in fact saw a 31% decrease.

The UK is third in the overall average citation impact (1.43), behind the US (1.46) and Canada (1.58), as seen in **Figure 2**. However, this impact has experienced a reduction in the past three years.

In 2019, the UK ranked first in terms of its category normalised citation impact, but this has now dropped from 1.58 to 1.16 in 2022. Canada, on the other hand, jumped by 111% from 1.24 to 2.60 in the same time period.

In terms of percentage of papers in international collaboration (**Figure 3**), the UK has continued to demonstrate and improve on its position as a global leader. As of 2022, 68.4% of the UK's publications were created in collaboration with international co-authors, a 5.8% increase from 2019. Other countries with a similarly high level of international collaboration include Canada, Germany and Spain.

These results indicate that the UK has remained an international leader in research on RAI in extreme environments Give the volume of public-ations emerging from the ISCF RAI-EE, it is possible to conclude that the programme has contributed this development.

Figure 10 – Number of Web of Science Documents
Source: Technopolis (2023), based on information provided by Clarivate.

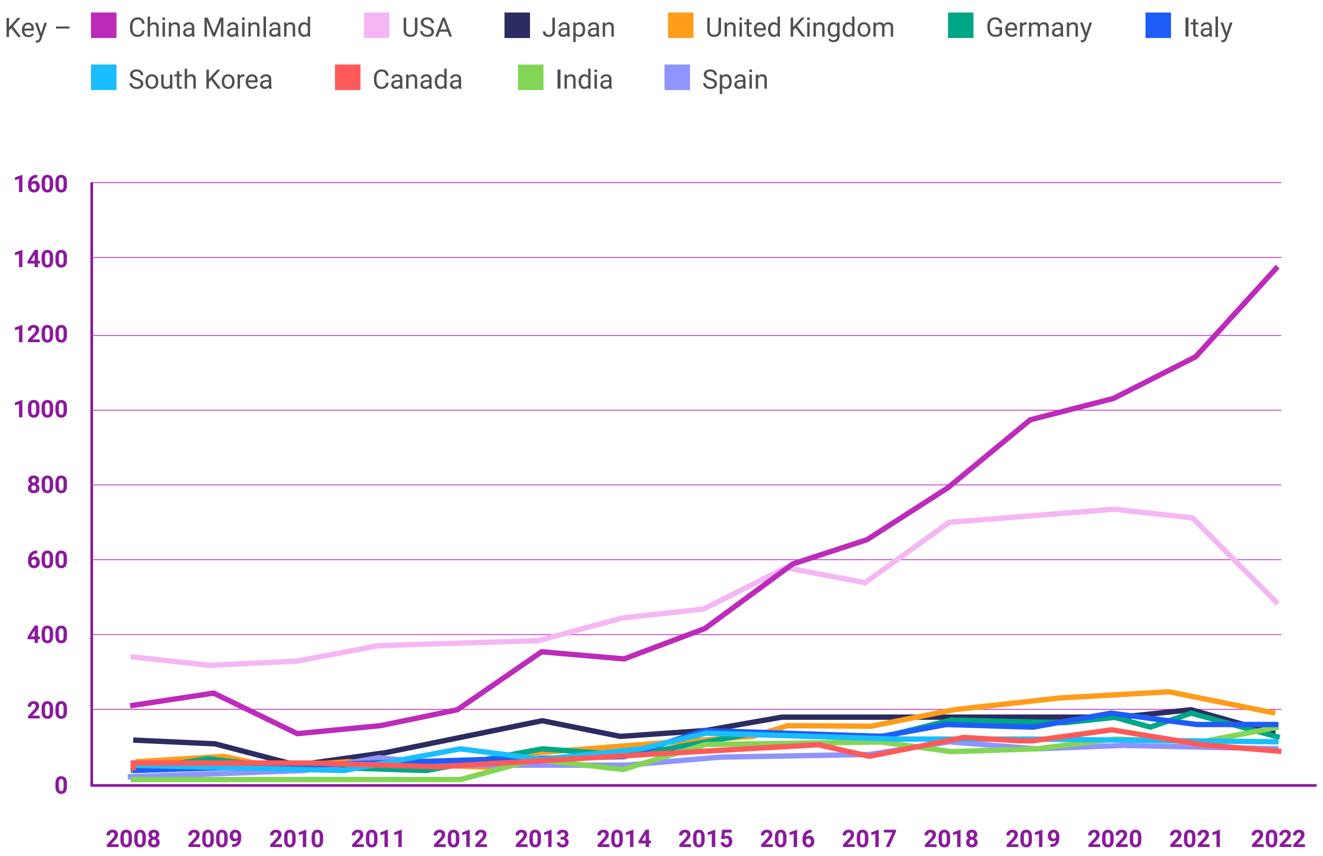


Figure 11 – (Categorised-normalised) citation impact (3-year average rolling window)
Source: Technopolis (2023), based on information provided by Clarivate.

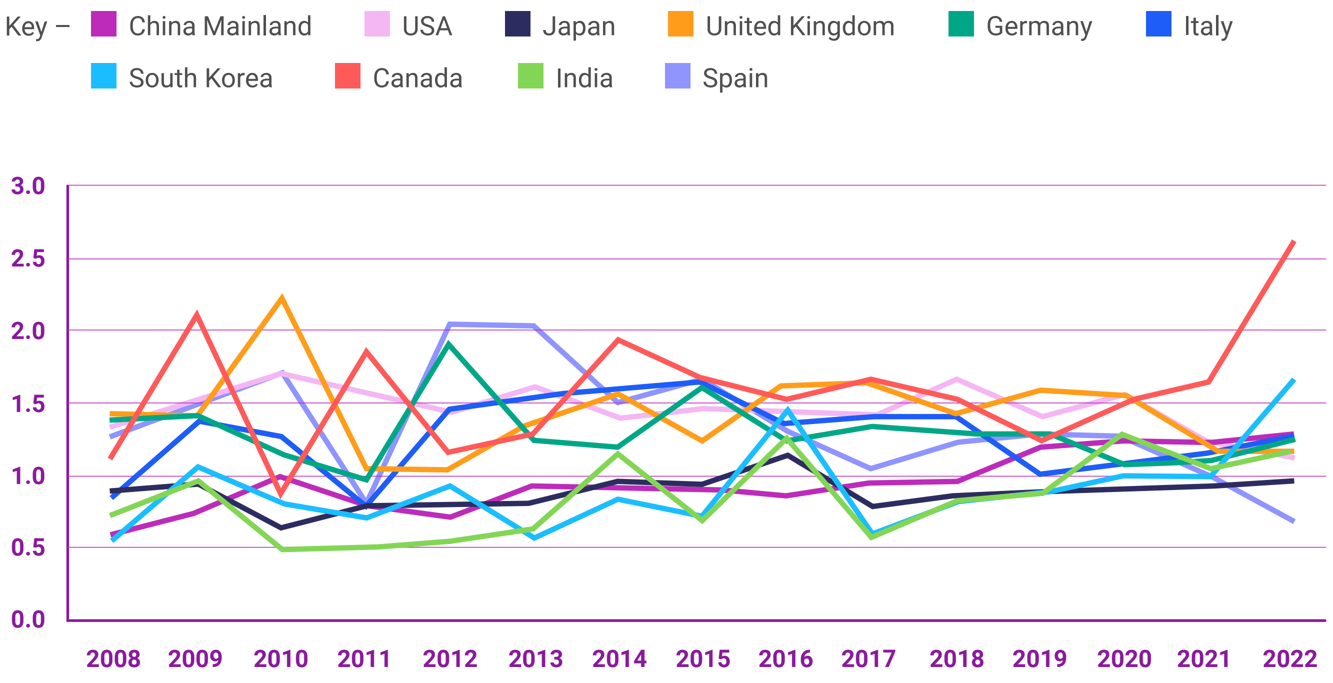


Figure 12 – Percentage of papers in international collaboration (3-year average rolling window)
Source: Technopolis (2023), based on information provided by Clarivate.

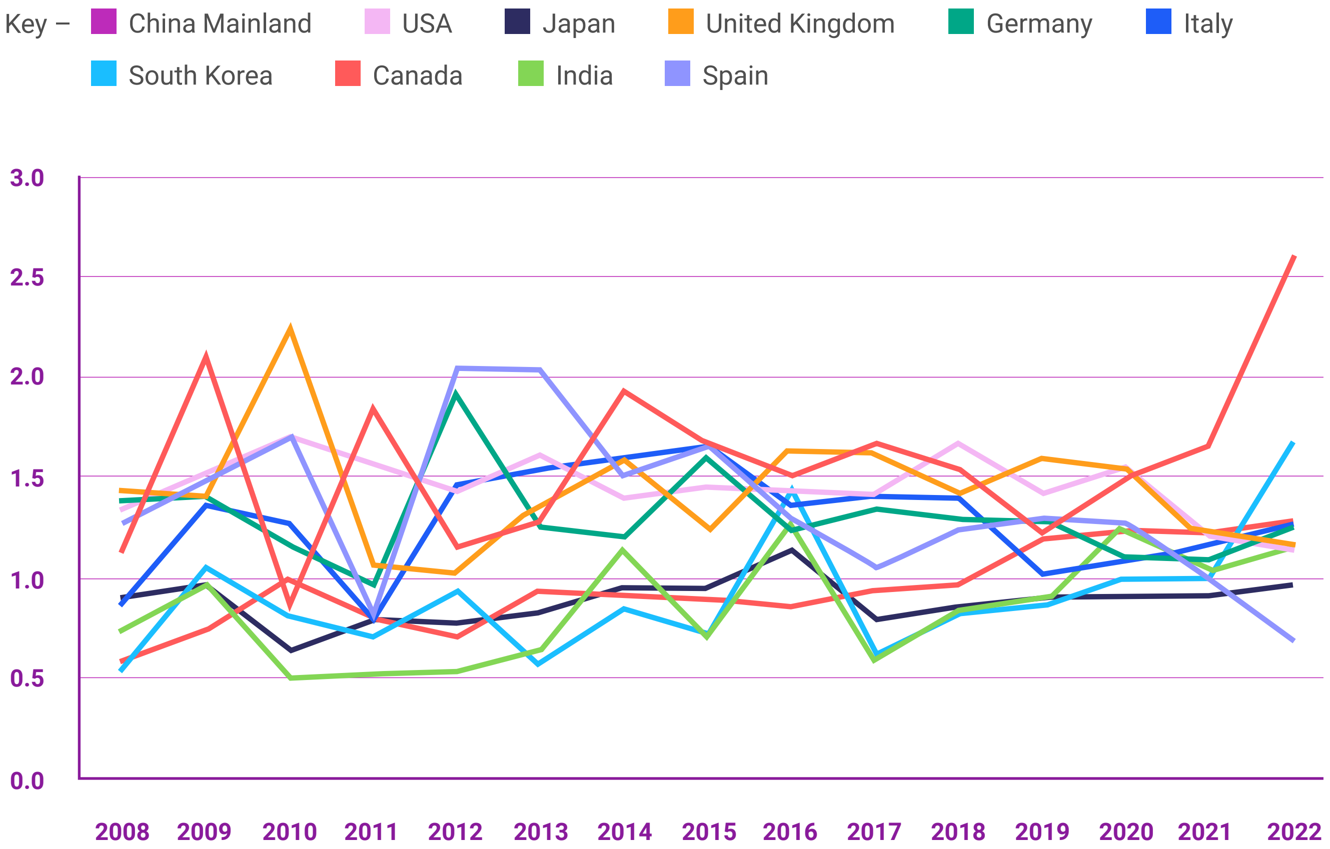


Table 17 – Bibliometric performance in the field of robotics in extreme environments research by country/region, 2008–2022
Source: Technopolis (2023), based on information provided by Clarivate.

Country/ Region	Web of Science Documents	Citation Impact	Category Normalised Citation Impact	Documents in top 10%	% Documents in top 10%	% International collaborations
China Mainland	8607	8.54	1.06	1061	12%	17%
USA	7501	14.05	1.45	1300	17%	28%
Japan	2208	7.16	0.9	234	11%	24%
UK	**2023**	**14.67**	**1.42**	**359**	**18%**	**57%**
Germany	1673	11.66	1.28	261	16%	49%
Italy	1634	10.7	1.28	268	16%	44%
South Korea	1312	8.97	0.94	134	10%	21%
Canada	1237	17.99	1.58	207	17%	51%
India	1071	6.82	0.94	112	10%	18%
Spain	1070	14.79	1.28	177	17%	54%

3.2.6 — Intellectual property

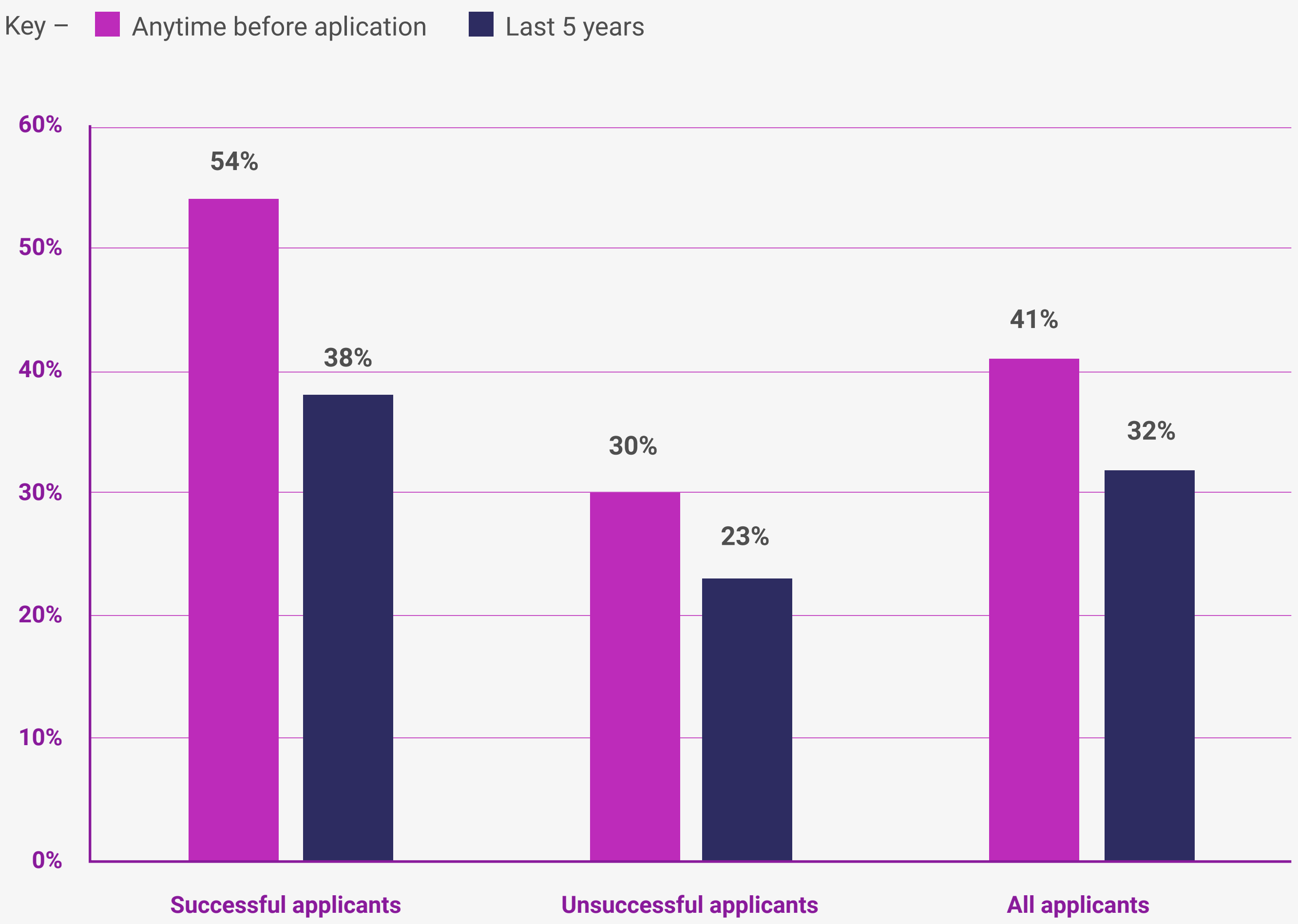
There has been limited activity in terms of intellectual property in the context of the programme, at least for the Hubs (based on ResearchFish data). Only one Hub (FAIR-Space) report patents applications. Including:

- The technology is a novel solution for portal device suitable for horizontal and vertical drilling with both terrestrial and space-based applications.
- A controller for the gripper being developed as part of FAIR-Space.
- A new tools for predicting sensors faults in autonomous cars.

In the final survey, 32% of businesses reported that in the last five years they had registered at least one patent relating to robotics in AI. Applicants for the extreme environments funding strands were asked to report only patents relating to the application of RAI in extreme environments. The average number of patents registered was 2.7. At baseline, 41% of this group had **ever** registered any IP relating to RAI or RAI in EE (when looking at a wider group of applicants – all who completed the baseline survey – this figure is 35%).

Figure 13 breaks this down by successful and unsuccessful applicants. Successful applicants were more likely than unsuccessful applicants to have registered IP prior to their application and also more likely to have registered it in the last 5 years.

Figure 13 – Proportion of applicants that had registered IP relating to robotics and AI (cohort: longitudinal). Includes non-EE applicants
Source: Final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base size: 85 applicants.



In terms of the wider landscape, we further investigate the UK wide activity in terms of intellectual property in the area of RAI in extreme environments. An analysis was carried out on a total of 7,680 DWPI patent families, invented since 2007, a 4,133 increase since the baseline analysis in 2018.

A DWPI patent family is a collection of all patents related to the same invention. Patent documents from 50 worldwide patenting authorities and 2 journal sources are reviewed for an invention and the data is compiled and presented in a concise DWPI patent family table. The DWPI Patent Family includes non-convention equivalents, which can originate from

applications that are filed by non-resident inventors in a country/region without claiming foreign priority, or applications that are filed outside the 12-month grace period (as stipulated by the Paris Convention).

In terms of volume, United States of America is most innovative countries in the technology domain, accounting for almost 57% of all inventions. The UK position has dropped to 6th position from 4th in baseline position, with India and Germany taking a lead.

UK patents made up 4.9% of the total, with 385 patents. While this is more than double the number of unique patents filed since 2018, this represents a slight decrease in global proportion from the baseline value of 6.1%. However, as demonstrated in Figure 4, a reduction in the number of patents has been the case for all of the countries involved in this sector, aside from India, which has seen over a 6% jump in proportion of patents.

Overall, the majority of the research is being performed by big players in the energy sector like Halliburton, Schlumberger, Aramco and Baker Hughes. Toshiba is the most innovative Japanese player, with several of its inventions related to its erstwhile subsidiary, Westinghouse Electric Company.

The leading entities from UK are Shell Oil, BP Plc, Subsea 7 Ltd, BAE Systems and Rolls-Royce. The average strength of 387 UK originated inventions have been reduced to approximately 35.36 (from 41.7) since our last reporting.

In term of strength and value of an inventions, we look at The Derwent Strength Index (DSI) assesses the strength and value of an invention based on characteristics such as frequency of citation, the breadth of geographic filing, existence and location of granted, issued patent rights, and the invention's technical breadth. **When comparing the average DSI between the countries (Figure 5), the UK is ranked fourth, behind India, the USA, and France. This suggests that while the UK may not be filing the same quantity of patents as other countries, the content is deemed at a similarly high value**.

The UK have continued to demonstrate a strength in offshore and deep-sea robotics, with a third of patents in each category. The majority of patents are filed for inventions relating to monitoring or sensors (44%) and remote-controlled robotics (34%). Over the last few years since the baseline analysis, the UK has diversified the type of inventions that are being developed in relation to RAI in extreme environments, with more patents filed in areas that were previously less common. The category that has seen the largest increase is Learning Platforms which has seen a 10% increase in its proportion of related patents. Another area of recent interest has been AI capabilities, indicated by an increase in patents associated with Neural Computing and AI Knowledgebase.

Figure 14 – Proportion of global patents
Source: Technopolis (2023), based on information provided by Clarivate.

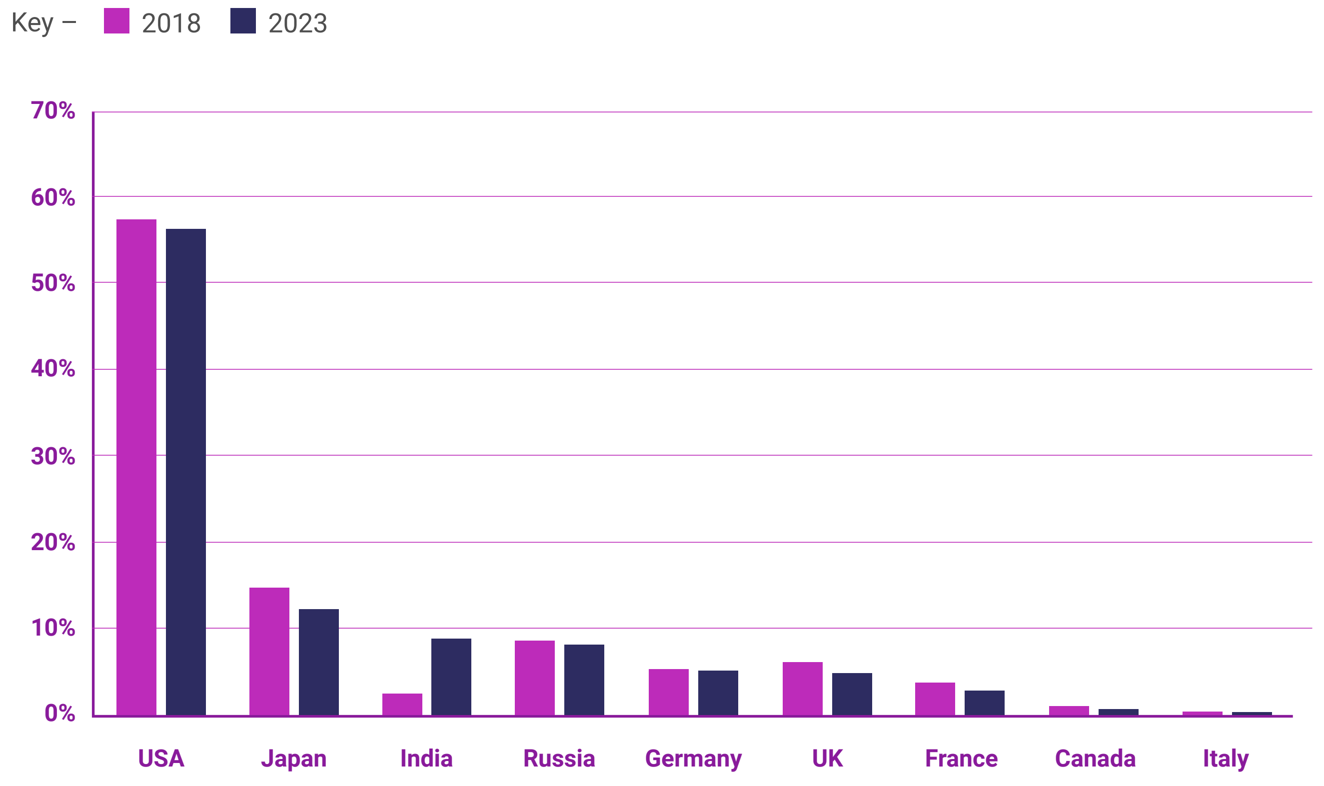
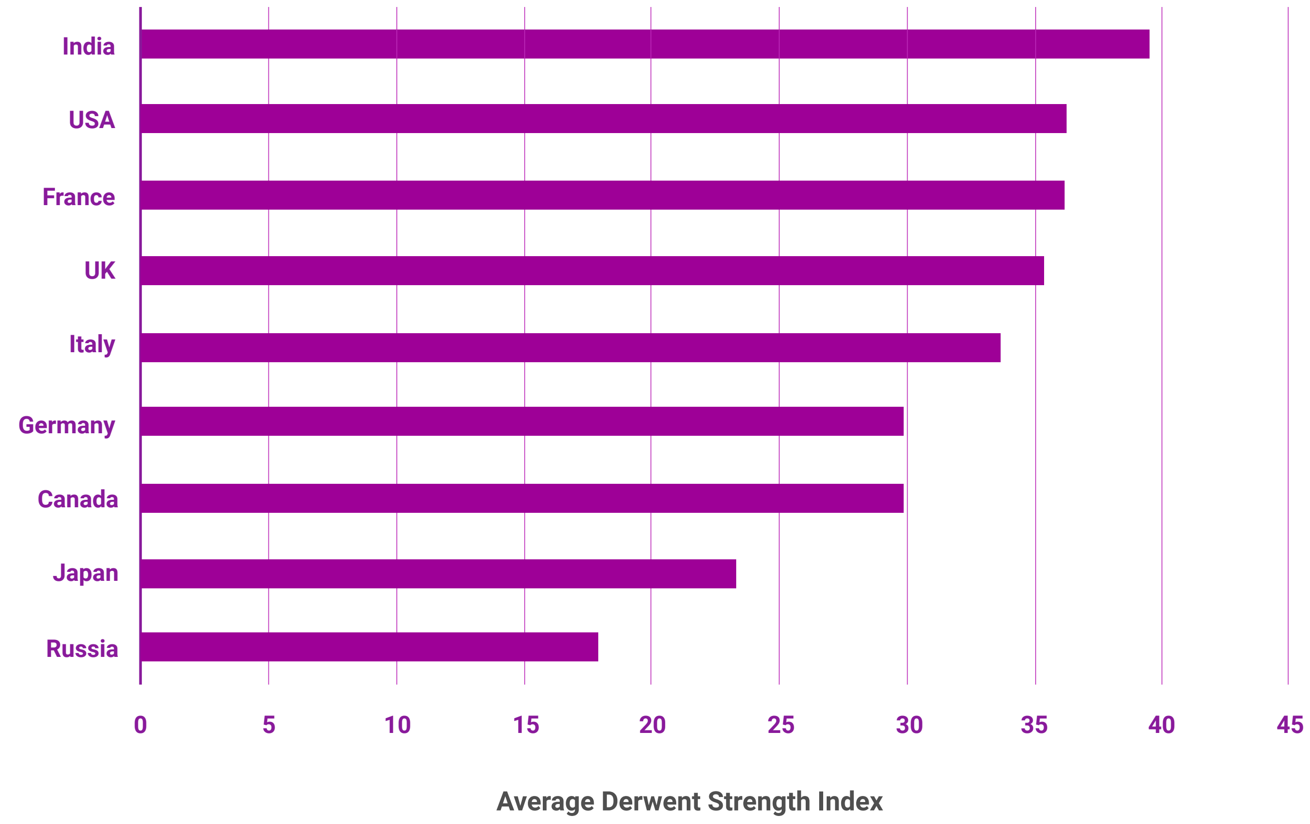


Figure 15 – Average Derwent Strength Index
Source: Technopolis (2023), based on information provided by Clarivate.



3.2.7 — Capacity building and absorptive capacity

Successful applicants surveyed by the evaluation[10] reported that as a result of the ISCF-RAI programme they had gained improved understanding of RAI solutions and the potential to apply them within their organisation, as well as improved internal capabilities to conduct RAI research.

Nearly all applicants (94%) said that taking part in the ISCF-RAI programme had improved their understanding of the potential for applying RAI solutions into their operations and processes, with three in five (61%) saying it had improved this to a great extent. A similar proportion (93%) reported that participation had led to improved skills and understanding of robotics and/or AI for extreme environments among researchers and management in their organisation. A sizeable majority (78%) also said that participation had led them to set up new plans and strategies to increase their adoption of robotics and AI, although only around one-third (35%) reported that the programme had influenced this to a great extent. Nearly all successful applicants (94%) also said that taking part in the ISCF RAI programme had improved their internal capabilities to conduct research into RAI, with around half saying it had done so to a great extent (52%).

In line with these findings, the case studies of innovation projects suggest that capacity building has been one of the main benefits realised by the partners so far. The case studies show that ISCF grants have enabled the industry partners to hire specialist staff, establish or deepen partnerships, gain access to testing facilities (e.g. through the catapults) and develop their business model, in several cases placing greater emphasis on software development (e.g. see HyBird below). In most cases, there is an expectation that this increased capacity may translate into economic impacts in the medium run, but this is difficult to predict (see below).

The case studies draw a straight line from the ISCF grant to the development of their business experiences by several grantees. It is clear that there are other factors and that not all these effects can be attributed to the ISCF, but it could be argued that ISCF grants were a necessary (although not sufficient) condition for these benefits to be realised.

Case study 5 –
HyBird

Source: Technopolis (2023), based on case studies.

HyBird aimed to revolutionise confined space entry by developing a high tech miniaturised smart robotic UAV capable of being deployed in an internal or confined space environment and undertake a mission autonomously. This would reduce the risk to personnel, increase productivity and provide substantial time and cost savings – that is provide companies with a safer, faster and cheaper solution to inspecting confined, extreme and challenging spaces.

The HyBird case provides a good example of capacity building (but also of collaborations, and potential for future growth). Successfully securing ISCF funding enabled the co-founders of HyBird to work on the business full-time, as well as build a strong technical team to achieve key milestones and outputs that was essential to the success of the project and for future business development and growth. Beyond this HyBird employed two software specialists, an AI specialist and a CTO.

As a result of expanding the team, the business leased bigger premises which included both office space and laboratory facilities. Throughout the project life cycle HyBird strengthened their partnership with Costian Ltd. The strength of the partnership was evident in the fact that HyBird and Costian continued to collaborate beyond project completion to maximise the commercialisation opportunities.

Furthermore, the funding successfully propelled HyBird into the Techstars Starburst Space Accelerator Program providing access to a range of industry and technology experts and mentors, which enabled the company to develop an invaluable network of advisors. At the time of the interim evaluation HyBird had in excess of 20 warm leads and soft commitments spanning the UK, the EU and the US, many of which were converted into hard commitments and further investment in HyBird.

3.2.8 — Adoption of RAI solutions

3.2.8.1 – Development of RAI solutions

The increase in the development of RAI solutions is one of the key objectives of the programme. Respondents (across all strands, including companies and academics) were asked how many new RAI systems and solutions they had developed, tested or demonstrated in the last few months.

We find that successful applicants have on average developed 4.0 new RAI systems and solutions, tested 4.8 and demonstrated 5 to potential customers and end users. This represents a notable increase in comparison with the baseline and interim positions (see **Table 18**).

Furthermore, the numbers of solutions developed, tested and demonstrated is lower among unsuccessful applicants and has declined over time. This is consistent with the results discussed on R&D investment.

This means that the programme has successfully supported the development of more RAI systems and solutions in comparison with the counterfactual scenario.

Table 18 – Developing, testing and demonstrating RAI solutions (all three strands, both academics and business participants) (cohort: cross-sectional)

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019 –Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base sizes: Baseline 96 successful and 61 unsuccessful. Interim: 104 successful and 51 unsuccessful. Final: 34 successful and 13 unsuccessful. All three strands, both academics and businesses. Extreme environments applicants only.

In the last 12 months, how many new systems or solutions relating to robotics and artificial intelligence in extreme environments has your research group/business ...? (mean)

	Developed		Tested		Demonstrated to potential customers or end-users	
	Successful	Unsuccessful	Successful	Unsuccessful	Successful	Unsuccessful
Baseline	2.8	1.5	3.0	1.6	2.6	1.3
Interim	2.9	1.6	2.8	1.6	2.5	1.3
Final	4.0	0.8	4.8	0.7	5.0	0.8

[10] These figures refer to 127 successful applicants, from all strands, surveyed at interim and final stage (for those who responded to the survey in both these waves, their most recent answer was used). Extreme environments projects only (equivalent outcomes for other projects are reported in 3.3)

Progression on the development of solutions is further substantiated by an analysis of TRL progression. Note that for the analysis presented in this section, the total number of projects has been kept constant across the baseline and final stages, and we have relied on the longitudinal approach to be able to assess progression within a comparable sample. Also, we have captured information on all robotics projects in extreme environments to be able to draw comparisons with the unsuccessful applicants. **Figure 16** shows that successful applicants' projects have moved towards higher levels of TRL, while new projects have entered the pipeline. Unsuccessful applicants had less projects overall a relative lower proportion of projects in the highest levels of TRL, but it is fair to say that the two figures do not show a clear pattern or clear differences in behaviour among those two groups. The analysis presented above is more straightforward in showing differences in terms of developing solutions and getting through different stages of development.

Figure 16 – Average number of projects at each TRL level (all three strands, both businesses and academics) (cohort: longitudinal)

Source: Longitudinal survey, baseline Nov–Dec 2018; and final Dec 2022–Feb 2023., Ipsos/Technopolis. Collective number of projects at each TRL level. Base: 27 successful applicants, 20 unsuccessful applicants (business EE applicants that answered this question at both baseline and final).

Key – Baseline Final

3.2.8.2 – Application of RAI systems and solutions

We explored the potential of applying RAI systems and solutions at interim stage (and exclude this from the final survey to shorten the questionnaire and boost response rates).

At the interim stage, we found that nearly all successful applicants across all three strands that identify themselves as end-users (94% of 115 surveyed) believed their involvement in the ISCF RAI programme had led to improved understanding of the potential for applying RAI solutions into their operations and processes. Four in five (81%) also believed that their involvement had led to new plans and strategies to increase the adoption of robotics and AI into their operations and processes. (Note that this data corresponds to the Interim Stage as end-users were not surveyed in the final iteration of the evaluation).

Survey respondents that operated in extreme environments most commonly used RAI technologies for inspection, followed by maintenance, decommissioning and clean-up, and communications. Expectations for how the technology will be applied in 2025 showed a large, anticipated increase in repair, construction and resource extraction applications, with transport applications expected to decrease and other types of application increasing slightly (see **Table 19**).

Table 19 – Areas of application (all three strands, end-users)

Source: Longitudinal survey, baseline Nov–Dec 2018; and interim survey Nov 2019–Jan 2020, Ipsos/Technopolis. Base: 43 respondents (non-applicants operating in extreme environments, and applicants to all three strands who consider themselves to be end-users of RAI in extreme environments).

Key – ↑ Increased ↔ No Change ↓ Decreased

In which of the following ways does your organisation apply robotics and/or artificial intelligence technology in extreme environments, and in which do you expect to apply them in 2025?

	Currently apply	Expect to apply in 2025
Inspection	74%	81% ↑
Maintenance	56%	65% ↑
Decommissioning	49%	60% ↑
Clean-up and waste management	49%	56% ↑
Communications	47%	58% ↑
Transportation of materials	44%	42% ↓
Repair	37%	65% ↑

In which of the following ways does your organisation apply robotics and/or artificial intelligence technology in extreme environments, and in which do you expect to apply them in 2025? (Continued)

	Currently apply	Expect to apply in 2025
Construction	26%	47% ↑
Resource extraction	16%	30% ↑
Other: Environmental sensing/ monitoring	9%	9% ↔
Other: Manufacturing components or tools	0%	2% ↑
Other: Military or defence roles	0%	7% ↑

3.2.8.3 – Readiness to adopt

Similarly to the above, we explored this aspect at the interim stage. When businesses operating in extreme environments were asked what barriers they faced to adopting RAI technologies more extensively in their operations, those most commonly cited were capital investment (by 26% of respondents), readiness of technologies (21%), client or customer attitudes to RAI (21%) and safety considerations (19%). Again, this includes all applicants across all three strands that identify themselves as end-users.

The baseline survey also showed higher levels of concern about workforce skills shortages and the lack of standards and certification than were reported in the Interim survey. Self-reported readiness to adopt RAI technologies more extensively did not appear to have increased significantly, although there were small increases in the readiness of technologies and in capital investment (see **Table 20**).

However, it is important to note that there is little overlap between the two groups of respondents in the baseline and interim survey.

Table 20 – Readiness to adopt RAI systems and solutions (mean value) (all three strands, end-users)

Source: Longitudinal survey, baseline Nov–Dec 2018; and interim survey Nov 2019–Jan 2020, Ipsos/Technopolis. Base size: Baseline: 44 end-user businesses. Interim: 43 end-user businesses (non- applicants operating in extreme environments, and applicants to all three strands who consider themselves to be end-users of RAI in extreme environments).

Thinking about the industry in which you operate, how would you describe your readiness to adopt robotics or artificial intelligence technologies more extensively in your operations in extreme environments. Please describe your readiness on a scale of 0 to 10, where 0 is not at all ready and 10 is completely ready, in terms of:

	Readiness of technologies	Workforce skills	Supply chain capabilities	Capital investment	Standards and certification
Baseline	5.2	5.4	4.7	4.9	4.2
Interim	5.6	5.5	4.9	5.3	4.4

Several case studies for demonstrator projects showed progress toward industry adoption, and in the development of their commercial models. Some projects have laid the groundwork to open up new sectors to the market, including complementary actors such as investors, insurers and regulators, and have already struck agreements with end users to pilot their technologies on a commercial basis (IOSCC). In parallel to expanding their technical capability and providing first-to-market technologies, project participants have also moved toward robotics-as-a-service models, unlocking new clients as a result (ROVCO). Participants have also been able to identify and build overseas markets where contexts are most relevant to their offerings (UAV Logistics).

However, the case studies also indicate that uncertainty on the end-user and regulatory sides remain a challenge to adoption. In some instances, participants have had to commercialise their technologies with restrictions placed on autonomous capabilities, with the expectation of unlocking these capabilities in the market after additional demonstration of safety and reliability to regulators in a wider range of real-world scenarios (UAV Logistics).

Case study 6 –

FAIR-Space hub and the Shadow Robot Company

Source: Technopolis (2023), based on case studies.

The FAIR-SPACE hub designed and implemented a robotic demonstrator to simulate in-orbit manipulation of both cooperative and uncooperative space targets. This allows simulating, studying and further developing three different space applications:

- In-orbit satellite servicing.
- In-orbit telescope assembly.
- Active debris removal.

The demonstrator brings together industrial and academic partners as well as different technologies relevant to the hub such as sensing & perception, robotics grasping and manipulation, as well as AI and developments in computer vision/perception. The demonstrator involved Shadow Robot Company and provided an opportunity to apply the company's technology inthe space sector for the first time. The case provides a good example of moving closer to the development of solutions that are ready for adoption.

The Shadow Robot Company's main business is the design and manufacturing of state-of-the-art anthropomorphic robot hands and related systems. Using Shadow's robot hand technology and an algorithm for Autonomous Visual Grasping (developed by Dr. Nikos Mavrakis at Surrey), they were able to pilot and showcase a demonstration of how an autonomous orbital robot could grasp the engine nozzle of a satellite.

Because the engine nozzle is part of both active and inactive orbital targets, this opens up other potential applications in the novel and under-explored field of robotic grasping for space applications, such as in-orbit servicing of satellites and active debris removal.

The company has also been actively seeking new markets for its products, including participating in a trade mission to the US in 2020. While the original focus has been on space, there is great potential to expand into pharmaceuticals and natural resource exploration.

The support of the programme, advancing its core development area has made this possible by demonstrating the potential and capabilities of the products.

3.2.8.4 – Views on barriers for the adoption of RAI systems and solutions

To complement the analysis above, in this final stage we further explored the issue of barriers for the adoption of RAI systems and solutions via stakeholder interviews and desk research.

The fundamental technologies that make up RAI systems are maturing fast, so that robots are capable of increasingly complex tasks. Their enhanced capability puts robots ever closer to humans and to strategic infrastructures, where they can take over dull, dirty and dangerous work, like monitoring nuclear facilities, or take on entirely new tasks, like decommissioning defunct satellites in earth's orbit. However, this proximity also reinforces the need for RAI solutions to be safe and reliable. This shift in focus is apparent in the patent landscape, where patents related to safety and reliability for RAI make up the majority in recent years for sectors like Offshore Renewable Energy (ORE).[11] Related to this, an overarching barrier to the development and adoption of RAI solutions mentioned in our case studies, by stakeholders from delivery partners and the industry, and further echoed in the wider literature is that of the novelty of these increasingly autonomous systems and the associated uncertainty about their safety and reliability.[12] This affects several stages and players along the journey to commercialisation.

For regulators, uncertainty means that RAI solutions must be rigorously vetted before certifying their safety for use amongst critical infrastructure or inhabited areas. However, there is little consensus on standard methods for certifying technologies like RAI, particularly those which incorporate machine learning and are designed for open-ended behaviour to deal with complex, real-world situations. Without regulation and standards to signal safety or to define liability, take-up for RAI remains low. For potential adopters of RAI solutions, uncertainty impacts the costs of finance and insurance. Investors and insurers, like regulators, require demonstration of safe operation before interest rates and premiums can be lowered to levels that can feasibly be incorporated into profitable business models. In many cases, though, the burden of uncertainty falls on innovators. Once their technologies progress beyond prototypes and approach commercial readiness, they must demonstrate safe and reliable operation within every conceivable environment and challenge the tech might face. This adds up to thousands of hours of testing. The facilities required to simulate real-world situations can be costly or inaccessible to innovators, particularly SMEs, posing a significant barrier to commercialisation. In a climate of uncertainty, innovators also run the risk of developing products only to have additional specifications imposed by a changing regulatory and financial landscape. The resulting hesitancy on the part of innovators to invest in expensive testing facilities further limits commercialisation.

In addition to uncertainty, implementation also presents several barriers to adoption. The upfront cost of RAI can be prohibitive given that solutions are often not off-the-shelf and require customisation e.g. training the AI or installing specific tools and sensors on a robotic platform.

Potential adopters may have concerns over ROI in these cases.[13] Another implementation challenge mentioned by our stakeholders is that of change and institutional inertia. When considering adoption of RAI systems, particularly those swarms or platforms designed to autonomise whole functions, the implications for an organisation's ways of working are significant. Autonomous functions may displace some teams, but they also require complementary functions to oversee them and integrate them with the rest of operations. As a result, organisations face both internal resistance and disruptions to business-as-usual. In this way an organisation's culture and appetite for innovation can hinder adoption.

[11] Mitchell, D, Blanche, J, Harper, S, Lim. Theodore, Gupta, R, Zaki, O, Tang, W, Robu, V, Watson, S, Flynn, D, 2022, **'A review: Challenges and opportunities for artificial intelligence and robotics in the offshore wind sector'**, Energy and AI, vol 8

[12] Kalra, N, Paddock, S.M, 2016, **'Driving to Safety: How Many Miles of Driving Would It Take to Demonstrate Autonomous Vehicle Reliability?'**, RAND Corporation

[13] Industry today, 2021, **'Challenges encountered in the Implementation of Robots'**

3.3 — Outputs and outcomes — focus on the 1-year extensions

3.3.1 — Projects focus

In 2020, largely in response to the COVID-19 pandemic, a one-year extension was devised to support robotics research in new domains. In contrast to the initially funded, core projects, the definition of extreme environments was expanded to include dangerous environments such as those in the construction or Agri-tech industries. The funding from the extension round was largely divided into three parts:

- Funding existing ISCF RAI projects that were impacted by the pandemic.
- Resilient future projects that supported projects in new areas, including agriculture, health, logistics and construction.
- COVID-19 fast start projects which were identified as part of Innovate UK's business led response to global disruption competition.

The outputs from existing projects largely mirror their original targets. For the majority of existing projects that received extensions, the added time and funding allowed them to make up for time lost due to restrictions during COVID-19.

For instance, **AutoNaut**, a company that designs, builds and operates uncrewed surface vessels (USV) to withstand the extreme environment of the Southern Ocean, eventually in winter, managed to complete its initial development during the original project period, but was unable to complete wider in-theatre testing. The project team was granted an extension to allow for a long endurance sea trial of the USV. Testing would also serve as a demonstration to potential users of its operation in an unsheltered open ocean without mothership support.

The extension allowed for the further development and integration of machine learning algorithms to detect and avoid floating small ice. Ultimately, the project was successful and the USV was able to operate independently for over 115 days while covering some 4000 nautical miles in the Atlantic. The success of the demonstration has generated significant interest from new stakeholders, selling five vessels to be used in science missions in the Southern Ocean and Caribbean.

As part of the reliant future strand, companies were identified that could have an impact beyond the core areas of the original programme. **Digital & Future Technologies** in collaboration with **Miralis Data Limited,** received funds to pursue UAV deliveries for vaccines and PPE with an automated loading and unloading system. This would allow a single drone pilot to pilot the vehicles in transit while allowing autonomous completion of the start and end delivery sequences. This has the potential to free up pilot time to oversee multiple aircraft in different phases across a wider logistics chain. In 2022, Miralis Data Limited received additional funds through the Future Flight Challenge, to further pursue NHS related UAV operations. The next project has the potential for completely autonomous UAV flights, when combined with the autonomous loading pursued in the ISCF RAI extension.

Mitigating disruption through robotic innovation was key to the development of the third component of the extension. With so much remote work being undertaken in 2020, there was a view that robotics and AI could assist industries that were essential but reliant on humans, such as chemistry or medical laboratories. One example of this is the ARC – Autonomous Research Continuity – project, which saw Arctoris Limited, Peak Analysis and Automation Limited expand their proprietary robotic and computational methods already used to deliver fully automated drug research for other life sciences applications. The funding allowed them to pursue this research and offer increasingly automated nation-wide support for life sciences research activity. Removing the human from this, increases accuracy, and allows for remote research to be undertaken even in complex circumstances. The utilisation of this technology has the potential to mitigate risksin future pandemics, making the sector more resilient, but also opening up new opportunities for research and collaboration.

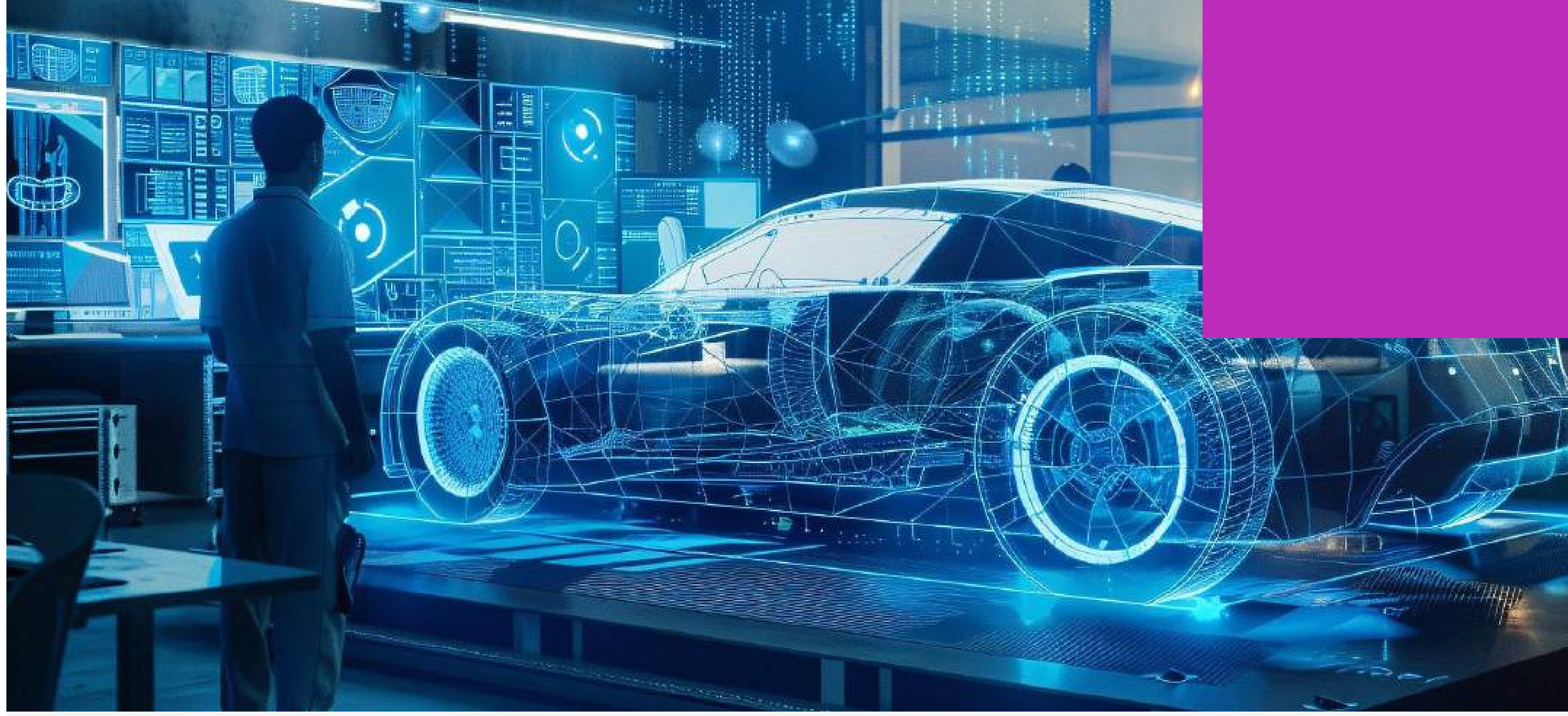
3.3.2 — Projects key indicators

In terms of key indicators, we find that:

- Project spend and R&D investment: Successful applicants had spent more on their projects as time has progressed in comparison with unsuccessful applicants, suggesting that the programme has leveraged resources in the areas covered by these calls. Furthermore, R&D spending in robotics and AI have remained constant among successful applicants but has declined unsuccessful applicants suggesting that the programme has protected R&D investment levels. R&D employment has remained the same across both groups, with a slight increase among successful applicants.
- Progress in projects: Successful applicants have made progress in terms of the technological maturity of their projects moving on the median, from TRL3 to TRL5. In contrast, the technological maturity of unsuccessful applicants' projects has remained unchanged (at TRL4). These results suggest the programme has successfully supported the progress towards commercialisation, but also suggest that most projects are likely to requireadditional resources (time, expertise, and financial investment) to further mature to the point of adoption.
- Economic outcomes: Notwithstanding the point above, the evidence also suggests the programme has had a positive impact on turnover related to RAI with successful applicants experiencing a median increase of £82.5k in comparison with the baseline position. In contrast, unsuccessful applicants experience a median increase of £62.5k in turnover related to RAI.

Table 21 – Key indicators: applicants to extension funds
Source: Final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: 16 successful and 22 unsuccessful applicants to the extension funds not related to extreme environments.

Type	Successful		Unsuccessful	
Median figures	At point of application	Final (Dec 2022 –Feb 2023)	At point of application	Final (Dec 2022–Feb 2023)
Project spend (final figure is cumulative)	£25,000	£125,000	£32,500	£75,000
R&D spending on RAI	£75,000	£75,000	£75,000	£25,000
R&D employment related to RAI	3	3.5	3	3
Number of R&D projects related to RAI	1	2	1	1
Project TRL	3	5	4	4
Turnover related to RAI	£40,000	£122,500	£10,000	£72,500



3.4 — Evidence of impact

3.4.1 — Economic

Economic effects of the programme (in terms of turnover and exports) are expected to materialise in the coming years once technologies are mature enough to be commercialised and generate income. However, at this stage we did expect to see progress towards this area of impact.

The evidence collected via survey shows mixed results for turnover, with a positive net impact when looking at most comparable cohort (i.e. longitudinal) albeit the usual caveats of the small sample and a zero net impact when looking at the other two cohorts (cross-sectional and mixed).

Table 22 shows that successful applicant companies have had a decline their average annual turnover of £0.9m between now and the baseline stage (based on results from mixed cohort). (Note that results in the interim stage and final stage may include their grant income, which for CR&D applicants is on average £0.16m per year of their project). **In comparison, unsuccessful applicants have had a decline of £0.8m in average annual turnover** in the same period of analysis. This suggests that the net impact of the programme on turnover is zero or close to zero (-£0.1m, obtained from comparing the change in turnover among the treatment and the control group). In contrast, a positive net impact is observed when comparing the other two cohorts (see **Table 23**) but at least in one case the difference is likely to be explained by the value of the ISCF RAI-EE grant.

Overall, this **let us to conclude that the programme has had limited or no substantial effect on turnover**. While many of the projects have seen advances in TRL over the course of this programme, most technologies are still not ready for full commercialisation. This means that although they are still developing and pursuing the technologies in question, improved turnover for supported businesses as a result of their participation is still largely a future prospect.

As observed in the case studies, the benefits to company profitability and turnover are limited. While some participants, such as Q-bot (Wormbot) and Aquanaut, have seen results from implementing their newly developed technology, this has not been observed more widely. In most instances, and particularly technology that has been developed within the Research Hubs, are still too nascent and low TRL to bring to market. It will likely require significant commitment of time and resources to see broad improvements in this area.

There is however one exception which was not capture via case studies or surveys, and it is the case of Wootzano, who has found commercial success albeit outside the extreme environment sectors. This case seems to be the exception and is presented in **Case study 7**.

Table 22 – Average annual turnover (all three strands, companies) (cohort: mixed)
Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019 –Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: 34 successful and 13 successful applicant businesses.

	Successful			Unsuccessful		
	Baseline	Interim	Final	Baseline	Interim	Final
Turnover derived from activities relating to robotics and artificial intelligence in extreme and challenging environments (Longitudinal data only)	£3.6m	£3.8m	£2.7m	£3.1m	£2.5m	£2.3m

Table 23 – Net impact on turnover (all three strands, companies)
Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019 –Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis.

	Net impact of ISCF RAI-EE on turnover [Tsuccessful(Final) – Tsuccessful(Baseline)] minus [Tunsuccessful(Final) – Tunsuccessful(Baseline)]	Number of observations
Mixed	-£0.1m	34 successful 13 unsuccessful
Longitudinal	£1.2m	11 successful 4 unsuccessful
Cross-sectional	£0.2m	**Baseline:** 50 successful 28 unsuccessful **Interim:** 48 successful, 22 unsuccessful **Final:** 34 successful 13 unsuccessful

Case study 7 –
Wootzano success story

Source: Technopolis (2023), based on information provided by UKRI, GtR and Companies House.

Wootzano Ltd is a start-up based in County Durham in 2018. The same year, they joined the ISCF RAI EE, via the Innovation Lab, as part of a large consortium to deliver the 'Multi-Platform Inspection, Maintenance & Repair in extreme environments (MIMRee)' R&D project.

In this project, they further developed their electronic skills. With two further IUK grants (including one from the 1-year extension under the ISCF RAI EE) they refined their system and have now developed an entirely autonomous robotic system capable of completing delicate, dexterous tasks like fruit and vegetable packing. Wootzano's technology allows its robots to have a greater sensory awareness of their environment by combining their patented electronic skin, proprietary hardware and machine learning algorithms in fully integrated robotic packaging systems.

In 2021, they announced an astonishing £300m+ deal to supply robots to fruit packing facilities.

Since the support provided by the programme (and due to their commercial success) the company has scaled from two to nine employees by three years (by end of 2021) and had 14 employees by end of 2022 according to Companies House.

Results on exports are negative across all cohorts, mostly due to a substantial increase in exports among the unsuccessful applicants. Table 24 shows that successful applicant companies have had an increase their mean export (as percentage of turnover) of 9 percentage points between now and the baseline stage (based on results from mixed cohort). In comparison, unsuccessful applicants increased exports in 23 percentage points in the same period of analysis. This suggests that the net impact of the programme on export is actually -5 percentage points (obtained from comparing the change in exports – as percentage of turnover – among the treatment and the control group).

Combine with the results above this will suggest that unsuccessful applicants did have a slight decline in turnover in this area (RAI in EE) but have been able to increase their exposure to international markets. This may suggest that successful have been more focus on UK end-users, perhaps due to the nature of the programme, but we do not have further evidence to substantiate this hypothesis.

Table 24 – Exports (all three strands, companies) (cohort: mixed)
Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis.

	Successful			Unsuccessful		
	Baseline	Interim	Final	Baseline	Interim	Final
Exports (as % of turnover derived from activities relating to robotics and artificial intelligence in extreme and challenging environments)	12%	23%	21%	9%	22%	32%

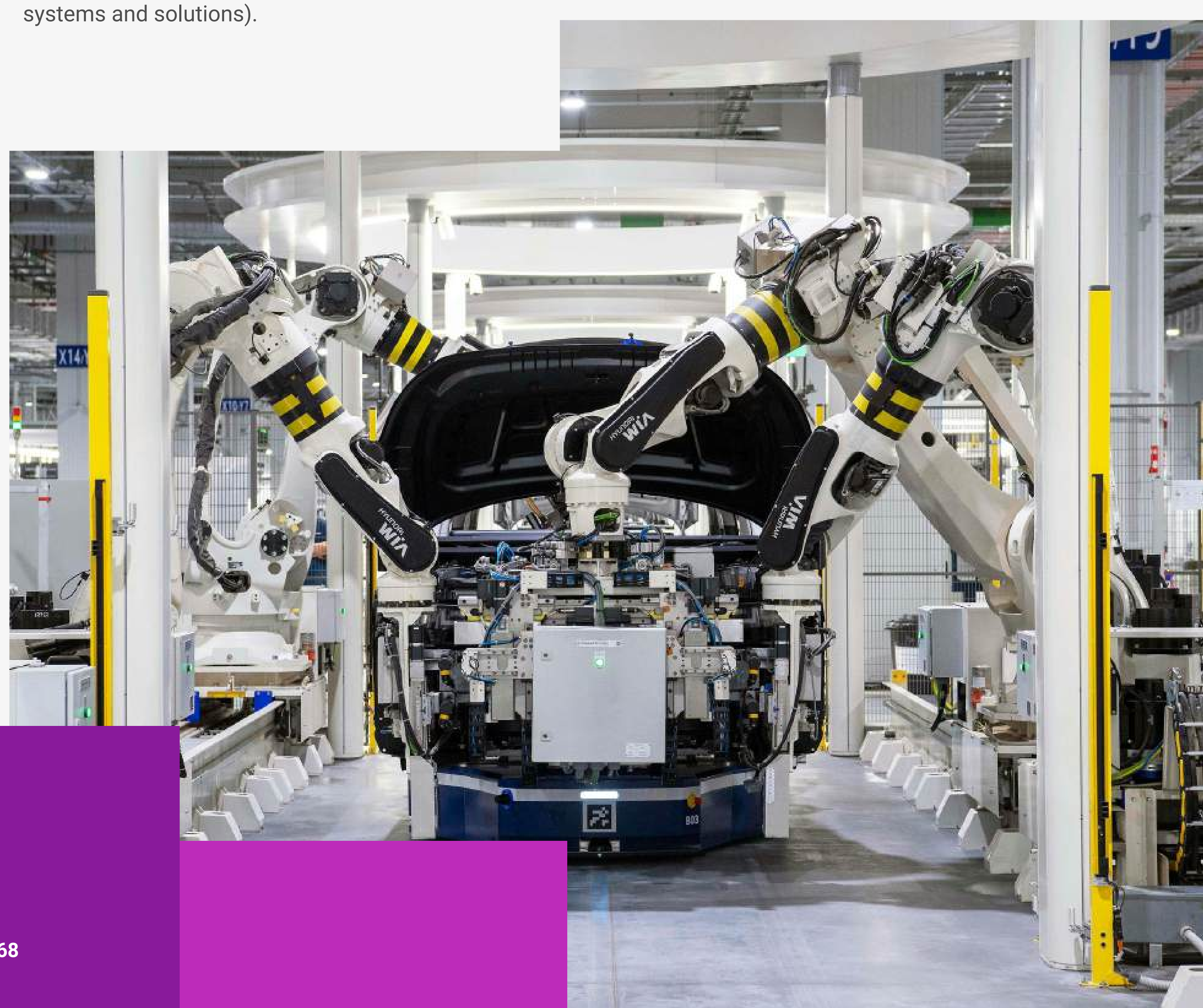
Table 25 – Net impact on exports (all three strands, companies)
Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis.

	Net impact of ISCF RAI-EE on exports [Esuccessful(Final) – Esuccessful (Baseline)] minus [Eunsuccessful(Final) – Eunsuccessful(Baseline)]	Number of observations
Mixed	-5 percentage points	34 successful 13 unsuccessful
Longitudinal	-30 percentage points	11 successful 4 unsuccessful
Cross-sectional	-17 percentage points	**Baseline:** 50 successful 28 unsuccessful **Interim:** 48 successful, 22 unsuccessful **Final:** 34 successful 13 unsuccessful

These results may reflect in part some of the issues flagged at the interim stage and related to adoption and readiness:

- Demand for RAI solutions is growing slowly due to the risk averse nature of the "extreme environment' industries. This is particularly important in the Nuclear sector, which – for safety reasons- tends to rely on the dependable and well tested approaches. There are also challenges of integration in that sector, as old/existing plants are designed around prior practices and it is hard to retrofit facilities to accommodate these new solutions, as well as the need to plan for disposal of (physical) solutions as these environments are extremely corrosive.
- Certification and standards remain a concern as solutions are bespoke in many cases, so the standards and calibration requirements are new.
- There is also a potential risk associated with the scalability of the solutions and the extent to which they can reach beyond a discrete number of end-users and thereby constitute a global market of sufficient scale to drive growth in the UK RAI-EE sector overall (of providers of systems and solutions).
- The uniqueness of some of the solutions developed under the programme, the retraction of R&D investment and turnover among unsuccessful applicants calls into question the commercial and investment appetite for these solutions in the wider market.

The case studies reveal some examples economic benefits, which vary in size and scope. For example, participation in the programme enabled ROVCO to commercialise their technology and diversify their service offering, which in turn has led to their expansion from 2 staff at the start of the programme to around 90 by 2023. Another programme participant, BML, are exporting their Panchito UAV to the African market where the technology's logistics capabilities are highly relevant. Lastly, the IOSCC case study (see **Case study 8**) shows the beginnings of potentially far-reaching economic benefits, particularly in the demonstration of a new market for in-orbit services, around which new actors can build novel services and products.



Case study 8 –

In-orbit Servicing Control Centre (IOSCC) National Facility

Source: Technopolis (2023), based on case studies.

The development of the IOSCC was a critical development in terms of commercial and national capabilities. The decision to fund the location is a key driver to grow the space services sector in the UK. The economic impact of this investment has been key for Astroscale, the commercial lead, who have been able to demonstrate capabilities of the centre and have won both further research projects and institutional clients based on this work. **It provides a good example of wider impacts of the ISCF RAI programme**.

The development of the IOSCC was a collaboration between the Satellite Applications Catapult, one of 9 innovation catapults created and funded by Innovate UK, and Astroscale, a Japanese company with a UK subsidiary established in 2017. With significant growth of the satellite market in recent years, and the upcoming launch of several large constellations by large firms (i.e. SpaceX and Amazon), there is increasing concern about how to address malfunctioning or failed satellites in the increasingly crowded low-earth orbit. The objective of the project was twofold:

- The first is a ground-based facility with the necessary functionality to monitor and communicate with assets in space that are. embarking on close-proximity missions.
- The second is an in-space demonstration of satellite capture and removal from orbit.

The IOSCC was successfully completed in time to act as ground control for its flagship mission. An operations centre equipped with fit-for-purpose hosting infrastructure and component redundancy was built. Among its comms assurance features, the centre monitors server and network health and is enabled for disaster recovery services. Computing capabilities have been upgraded to handle high speed video image processing, and remote access to space-based assets is protected by appropriate cybersecurity measures.

ELSA-d, the Astroscale in-space demonstration, with IOSCC providing ground control capability, has received international recognition for its contribution to space sustainability. Among its awards:

- 2021 Satellite Technology of the Year, as part of the Via Satellite Awards at the SATELLITE 2022 Conference and Exhibition.
- Minister of State for Space Policy Award, sponsored by the Government of Japan's Cabinet Office.
- A special mention by the UK's Science Minister in a speech presented in Japan.

The IOSCC project has led to follow on activities for the Catapult and for Astroscale. The Catapult is currently in talks to host a handful of active debris removal (ADR) projects through the UKSA Fund, many of which are being led by private operators like ClearSpace and Space Forge. The Catapult's involvement in the In-Orbit Servicing and Manufacturing Group and the Space Energy Initiative were also the result of IOSCC participation. These groups eventually led to the creation of Space Solar Ltd, which aims to deliver space-based solar power commercially within the next decade.

For Astroscale, the successes and lessons learned from ELSA-d have led directly to a follow-on mission with commercial promise; ELSA-M (Multiple client). Designed for 9 years of service without refuelling (the useful lifespan would increase with the possibility of future refuelling and recycling missions), ELSA-M is Astroscale's flagship End-of-Life service. OneWeb is the prime for an ELSA-M In-Orbit Demonstration (IOD) mission with partial funding from UKSA and ESA. Expected to launch in 2025, the ELSA-M servicer is on track to be the world's first commercial venture designed to capture and remove failed satellites and dispose of them safely.

3.4.2 — Societal

As per our Theory of Change, **societal impacts** are only expected to materialise in the future (following the commercialisation and adoption of solutions developed through the programme). As such, there is no concrete evidence at this stage of societal impact having been achieved.

However, our case studies suggest that, in the future, one of the main areas of impact expected concerns the safety of personnel involved in the operation and maintenance of facilities in extreme environments. This would be primarily achieved by replacing humans with autonomous robotic systems, for example in nuclear decommissioning (RAIN and NCNR), inspection of offshore assets (e.g. ROVCO and RADBLAD), and supporting safer and less disrupted railway infrastructure (e.g. Prometheus).

A number of case studies, especially those related to the offshore wind sector, also expect to contribute to the reduction of carbon emissions and thereby the mitigation of climate change (e.g. HyBird, RADBLAD, Wormbot).

Case study 9 –

NCNR hub — Robotic cutting and sorting of radioactive material

Source: Technopolis (2023), based on case studies.

Working with NNL Preston Laboratory at their Springfields site, the Director of the NCNR hub, Professor Stolkin, has worked to develop an AI enabled vision system to allow robotic cutting and sorting of radioactive materials. This project involves using AI vision to identify shapes and materials, lasers to cut through steel and concrete, and robotic grasping to hold and sort materials.

Over the next 100 years, the UK is expected to generate upwards of 4.9m tonnes of nuclear waste. With present technology, it is expected to take up to 120 years to complete the clean-up and cost upwards of £200bn. Currently, when humans are involved in nuclear clean-up operations they must be kitted out in air-fed plastic suits with multiple layers and thick gloves.

This makes the operation cumbersome, physically taxing, and dangerous. The risks to humans means that this work can only be undertaken for short periods. The use of robots in decommissioning has the potential to mitigate the exposure to humans while being able to be more efficient simultaneously, thereby reducing costs as well.

As nuclear legacy sites are unstructured environments, cutting robotics need to allow for variations and differences in the material properties (e.g. size and shape), particularly where these properties may not be documented exactly or are affected by degradation (due to radiation, corrosion and ageing). In the case of nuclear decommissioning, the exact cutting path of the laser is not important so long as the pieces are made smaller or allow for a containers' contents to be inspected. As a result, the cutting path of an autonomous robotic system must be planned in near-to-real time based on both the shape of the object, the positioning and manoeuvrability of the robotic arm holding the laser cutter, and the need to avoid any obstacles. Pre-existing path planning algorithms were unable to fully meet this diverse set of needs.

The potential societal impact of this work is around limiting the involvement of humans in the cutting and sorting of nuclear waste. The integration of robots, capable of cutting and sorting hazardous material into smaller pieces, capable of being managed more safely, means that humans are only involved in more controlled situations, improving the safety and working conditions required in decommissioning.

The research funded as part of the NCNR, has continued apace, with new outputs and tests taking place. The results of the research have also been fed into the international Nuclear Energy Agency planning for future nuclear decommissioning activities.[14] Ultimately, this work will support the drafting of regulatory frameworks that will determine how robots will be included in future nuclear decommissioning.

As reported at the interim stage, there are also some signals of positive spillovers in terms of policy influence. Three of the Use-inspired Research Hubs are members of two British Standards Institution committees[15] and to two IEEE Standards Association committees.[16] These committees are working to provide national and international methodologies and tools for the development, implementation, use, and assessment of robotics and autonomous systems. RAIN Hub has also been working with Office for Nuclear Regulation and Culham Fusion regarding future regulation of nuclear robotics.

According to ResearchFish, the ORCA Hub has been very active in developing wider policy links. For example, researches within ORCA were involved in the planning and development of the proposed Robotics Sector Deal, and have also been active in providing evidence and meeting with government ministers and civil servants around the UK Maritime Strategy and drone legislation. Representatives of ORCA also sit on two international advisory committees.[17]

3.5 — Conclusions and lessons learned

3.5.1 — Conclusions

Overall, the findings indicate that the programme has contributed positively to the majority of expected outputs and short-term outcomes, including advancements in academic outputs and the maturity of technologies developed within the projects. Additionally, there have been positive benefits in terms of R&D employment in RAI in extreme environments. Evidence also suggests that support from the programme may have helped to maintain levels of R&D investment in RAI in extreme environments within participating organisations (but results need to be taken with caution given number of observations), and attracted private investment from venture capitalists.

There is less progress in terms of commercialisation and adoption of RAI solutions. This is perhaps expected given the maturity of the technologies supported (which have made progress but are still not close to market) and the time required for these technologies to transition into commercialised applications. Other factors hindering commercialisation include barriers to adoption among end-users (due to factors ranging from internal skills to regulatory barriers), as well as the relatively small market opportunities for certain solutions, such as those pertaining to Nuclear and Space industries.

Table 26 shows a summary assessment of the key expected outcomes and benefits from the programme.

[14] Nuclear Energy Agency (2023). **Status, Barriers and Cost-Benefits of Robotic and Remote Systems Applications in Nuclear Decommissioning and Radioactive Waste Management**

[15] KBSI standards committees for Robotics (AMT/10) and its sub-committee for Ethics for Robots and Autonomous

[16] IEEE committees for Standard for Fail-Safe Design of Autonomous and Semi-Autonomous Systems (P7009) and Standard for Transparency of Autonomous Systems (P7001)

[17] Scientific Advisory Board of the French Oceanographic Fleet and the Jiangmen Science City Foundation

Table 26 – Summary assessment of key expected outcomes and programme benefits
Source: Project data.

Key –

Widening of UK's R&D capability and capacity in RAI for extreme, and challenging environments	Supporting the development of market ready RAI solutions for extreme environments
Improved connectivity between research and industry	Progress against Technology Readiness level
Improved skills and capabilities	Adoption of RAI solutions (developing and testing solutions)
Increased volume of excellent research	Adoption of RAI solutions (adoption by end users)
Increased R&D investment in UK RAI-EE	Improved business performance
Increased R&D employment	
Increased private investment in UK RAI-EE	

As per our Theory of Change, **societal impacts** are only expected to materialise in the future (following the commercialisation and adoption of solutions developed through the programme). As such, there is no concrete evidence at this stage of societal impact having been achieved. However, our case studies suggest that, in the future, one of the main areas of impact expected concerns the safety of personnel involved in the operation and maintenance of facilities in extreme environments. This would be primarily achieved by replacing humans with autonomous robotic systems, for example in nuclear decommissioning, inspection of offshore assets, and supporting safer and less disrupted railway infrastructure.

The case of Wootzano and its highly dexterous robots for fruit and vegetable packaging could also help reducing problems related to shortage of labour and well as costs (with still unclear effects on net employment).

As reported at the interim stage, there are also some signals of positive spillovers in terms of policy influence, with representatives of various Use-inspired Research Hubs sitting in different committees that are working to provide national and international methodologies and tools for the development, implementation, use, and assessment of robotics and autonomous systems.

3.5.2 — Leassons learned and recommendations

For actors in the actors in the RAI industry

A number of **themes emerged from the case studies and stakeholder consultation, many of which offer lessons to actors in the RAI industry**.

- **"Valley of Death 2.0"** – The Valley of Death describes new technologies that fail to make the transition from the lab to a working prototype (TRL 4–6). However, for RAI solutions with strong elements of autonomy there exists another critical transition, or "Valley of Death 2.0". This is largely due to an uncertainty loop[18]: we can't know how safe or reliable autonomous machines are without using them and generating supporting data, but we are restricted in our use of them because regulators don't know how safe they are. The need for supporting data means that prior to full commercialisation, RAI systems must be tested in a large variety of conditions while circumnavigating a number of scenarios, both likely and unlikely. Proving that the probabilistic decision-making of AI (as opposed to the deterministic logic of classical software) is reliable in any circumstance presents significant testing and demonstration costs to innovators and necessitates access to funds and high-tech facilities. Without these, RAI solutions get stuck around TRL 8–9. There is a significant role for governments and financiers to play in ensuring that innovators, particularly SMEs, are provided access to the means of demonstrating their technologies.
- **Robotics as a service** – Firms in the RAI industry are adapting their business models from technology development to service provision. Such firms retain ownership of their robots and are involved in the development, customisation, deployment, maintenance and decommissioning of their fleets. For those clients who do not wish to invest in robotic fleets of their own, who require a diverse range of capability or who do not possess the internal capacity to programme their fleets, robotics as a service presents an attractive option and increases their likelihood of adopting AI. However, this model works better in some sectors than others, and there are still clients who prefer to own their RAI assets outright.
- **Institutional inertia** – Some of the organisations with the greatest potential for RAI often lie in the public sector thanks to their buying power and stakes in assets and facilities where robots could prove most useful. However, these organisations are not monoliths and enthusiasm for robotics at a high level does not necessarily translate into adoption. Their appetite for large, disruptive projects that overhaul their operations is lower than in profit-driven organisations. For innovators, the public sector may represent an attractive market, but they must remain cautious when developing solutions aimed here.

On programme design

- As suggested in Process evaluation report (2019) future iterations of the programme with a challenge driven approach could consider strengthening cross-fertilisation across strands via dedicated measures (e.g. special call for proposals), understanding the need to maintain a balance between its support for a core group of organisations and the need to remain open to new ideas from outside the mainstream. Evaluations of other ISCF programmes (Audience of the Future, Next Generation Service) have demonstrated that this is possible but requires ring fencing resources at the outset, to make further investment decisions as the programme progresses.
- The evidence collected across the different phases of the study shows that pre-existing partnerships were seen as crucial to successful project implementation and attainment of results. We recommend that future iterations of the programme take this into consideration, e.g. by providing extra marks to applications that are able to demonstrate prior knowledge/experience working together and/or by sharing information on lessons learned on collaborations (in particular industry-academia) with new partnerships to speed up their process.

[18] Kalra, N, Paddock, S.M (2016) **'Driving to Safety: How Many Miles of Driving Would It Take to Demonstrate Autonomous Vehicle Reliability?'**, RAND Corporation.

On Robotics & AI in extreme environments as an investment area

- Our research confirmed that there are several major barriers that will continue to hamper adoption of RAI-EE even where the solutions have been proven to be cost-effective: prospective UK customers remain cautious around capital investment and there is also a wariness around the movement to these novel technologies. Client attitudes tend to be highly risk averse in all of these safety critical areas: offshore, nuclear and space, for understandable reasons. Future programmes may consider funding follow on activities that bring researchers and innovators closer to regulators and end-users via for instance regulatory sandboxes and demonstration in real world conditions.
- There is also a potential risk associated with the scalability of the solutions and the extent to which they can reach beyond a discrete number of end-users and thereby constitute a global market of sufficient scale to drive growth in the UK RAI-EE sector overall (of providers of systems and solutions). As a case in point, the strongest commercial success has been found so far in areas of application outside extreme environments. Future programmes may consider expanding their initial research into the size of the commercial opportunity offered by supported sectors.

On Monitoring and Evaluation

- Programmes supporting Research Hubs should consider requiring these Hubs to catalogue a list of projects/technologies to inform the understanding of their achievements of producing 'project level' indicators (including those related to progress on technology readiness level and on potential uses and commercial opportunities), similarly to what we were able to do for the CR&D and Demonstrator projects.
- More generally, we also suggest gathering additional intelligence about the projects'/participants' next steps after the completion of their grants, via the project completion forms.
- We suggest UKRI take note that there are trade-offs in the timing of the final evaluation. The more time that passes the higher the degree of attrition for primary data collection (as people move between roles, jobs and/or organisations), but the higher the probability to detect medium to long term outcomes. Our recommendation is that the final phase does not take place more than 6 months after the projects end, particularly if there is not follow on funding.
- We also recommend that multi-phased evaluations include a Process Evaluation in the first and last phase of the studies (and that this is resourced accordingly) to update the knowledge and understanding of the extent to which the process (specifically programme design and delivery) supported the attainment of expected outcomes.

Appendix A

Process evaluation (2019)

As part of the ISCF RAI in EE evaluation, we conducted a Process Evaluation in 2019. The main conclusions and recomendaitons from this evaluation are presented below for completeness.

A.1 — Conclusions

The programme responds to the UK's strategic ambition of strengthening our position in a growing global market (Robotics & AI) targeting emerging sectors where the UK has particular 'natural' assets and industry capabilities (extreme environments).

The relative specialism of these applications, and the lack of any pre-existing dominant suppliers (unlike in industrial robots), presents a good opportunity for the UK, with its relative strengths in each of these markets. The programme's sharp focus on these niches is appropriate and means its £93m public investment could make a tangible difference to UK competitiveness in the area.

The ISCF RAI-EE programme has been designed explicitly to address the principal market failures identified in the business case. If there is a caveat as regards the appropriateness of the programme design, it is the scale of the resources on offer. The ISCF RAI-EE programme design and objectives fit well with the view of the programme management team and the ambitions of the project participants, which collectively endorse the need for increased investment in RAI related research and collaboration with industry and end-users. This is seen as necessary to advance the underpinning technologies, build and demonstrate workable solutions and showcase those solutions to prospective investors and end-users.

The ISCF RAI-EE programme governance structure is appropriate to provide the oversight and leadership necessary to ensure the programme is delivered effectively. It has a similar governance structure to the other ISCF programmes, with the ISCF RAI-EE programme board reporting to the UKRI ISCF board, while overseeing each of the three individual programme strands (Hubs, CR&D, Demonstrators). The RAI Challenge Director and Programme Board benefit from the independent advice of the RAI Challenge Advisory Group.

There are areas where some small improvements in the governance arrangements could be beneficial:

Coordination across strands has been limited to date, in part because the three strands were launched together. We would expect to see greater interplay between the three strands in the later stages of the ISCF RAI-EE programme, especially as the Hubs manage to progress their research agendas and the first RD&D projects reach their conclusion (see sub-section below for recommendations on how to strengthen this interplay, going forward).

The ISCF RAI-EE programme is a useful additional investment in a key technology area that dovetails well with the various other UK government initiatives with an interest in robotics and AI, whether that is support for robotics and AI as an underpinning technology or the development of robotics for use in more mainstream applications (e.g. Industry 4.0). The programme is investing in RAI for extreme environments on a scale never seen before and this focus is also quite distinct when compared with the majority of other investments which have focused to a greater extent on other application areas in industry, agriculture and healthcare. It has broadly doubled the annual volume of public funding available for research in the area of Robotics and AI in extreme environments, while also triggering additional investments through our UKRI sources and broadening the range of research and innovation activities supported.

As regard to processes, and in terms of early engagement, the ISCF RAI-EE programme made good use of existing Innovate and EPSRC networks and communications channels and was able to quickly raise awareness and generate interest among the relevant academic and industrial communities, as well as multiple communications channels. The great majority applicants – successful and unsuccessful – were satisfied with the clarity of the information provided about the calls.

The selection processes for the Hubs and for the Collaborative R&D projects and demonstrators have largely followed well-established procedures.

In the case of Hubs, the selection criteria and process seem fit for purpose, as the selected Hubs clearly align with the target areas of the challenge. For our side, further improvements could be achieved by a round of due diligence process and monitoring.

In the case of the CR&D and Demonstrators, again, the selection criteria and process seem fit for purpose; however we see value in adding a question or two in Section 6 (wider impact) in future iterations of the programme, inviting applicants to specifically reflect on how their projects fit in a 'challenge driven' programme and how they could be game changing for the 'industry' (either the RAI industry or the end-users in the extreme environment sectors).

The relatively small number of applications to the first call is arguably a result of the relatively short time that passed between the initial announcements and the deadline for the call. The majority of proposals came from established robotics research groups and businesses, again reflecting a readiness to respond. The average score of the proposals attracted was, however, slightly lower than a comparable Innovate UK call. The communications team is working hard to broaden awareness as shown by the level of interest in the Innovation Lab. The novel and narrower focus of the calls may also be a factor in the level of interest, however, this should improve over time as the existing robotics community gears up to the opportunities available and newer constituencies are mobilised.

Analysis conducted by the study team shows that the programme has attracted actors from across the robotics & AI supply chain, from component/technology providers, to system integrators, intermediate companies, and public and private end-users, which is very positive. We also found that the programme has also attracted applications from the key sectors.

Overall, the monitoring system is working reasonably well. From an operational perspective, the monitoring and reporting process provides the information required by the Board and programme management team to track finances and project progress as well as any particular financial and technical risks identified. The system is well established and works seamlessly for the CR&D and Demonstrator strands. The Hubs are more complex structures and their reporting activities are at one more involved and harder to calibrate and the programme management team has to work harder to arrive at conclusions as regards to progress.

A.2 — Recommendations

Producing a Value for Money assessment – No value for money ('Green book') appraisal was made for the ISCF RAI-EE programme (or its strands). This is not unusual within the context of research and innovation policy, however, it means that the expected value for money of the ISCF RAI-EE programme it is unknown and not available for external scrutiny. Also, the relatively low demand for the competitions under the programme pose some questions around the strategic case to invest in this area, that could be countered by this type of appraisal.

It is perhaps too late to address this issue fully for the ICSF RAI-EE programme, however, it would be helpful if future ISCF programmes were required to complete a more robust, ex-ante appraisal. For the current programme, there would still be value in the Programme Board looking to its Advisory Group and major investments (Hubs) to help it develop a fuller elaboration of its strategic case for investment. A more detailed review of the overall strategic and economic potential of the intervention would be of value to both programme oversight (steering, tracking progress).

Keeping a good overview of other government initiatives to further capitalise existing investments – As mentioned above, we have identified tens of departmental strategies, sector strategies and place-based innovation strategies that are looking to champion the development of novel RAI applications of relevance to their particular interests (albeit little in extreme environments). We recommend the ISCF RAI-EE programme management team carry out a more substantive review of wider policies and strategies here in the UK and internationally, in order to provide the programme management team and its Advisory Group with a fuller exposition of the parallel initiatives where there might be opportunities for follow-on funding, networking and showcasing of programme achievements.

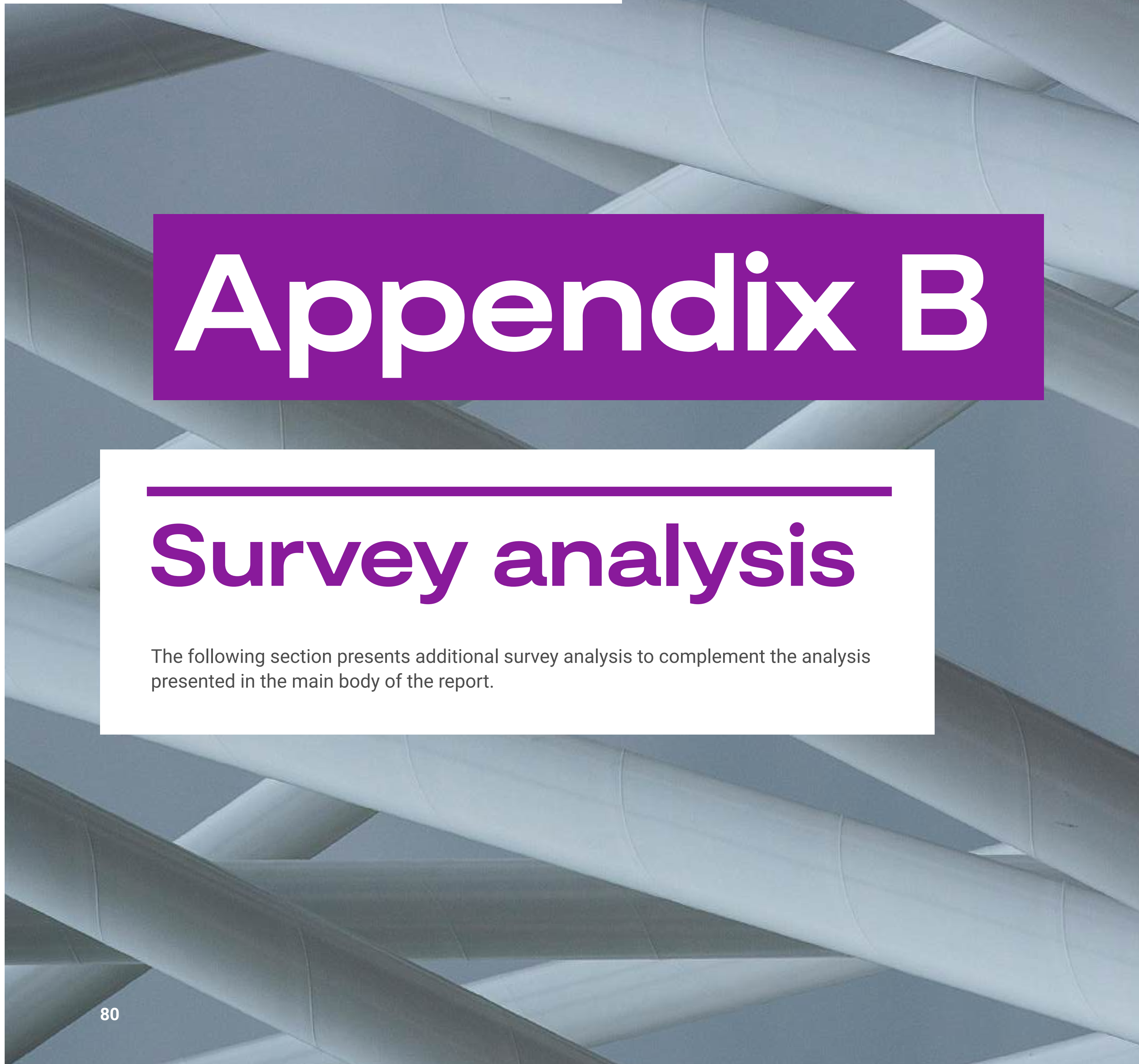
Further improving transparency and diversity of Boards – The RAI programme governance structure is appropriate to provide the oversight and leadership necessary to ensure the programme is delivered effectively. There are areas where some small improvements in the governance arrangements may be beneficial, including the publication of the two governing bodies' memberships and terms of reference online to improve transparency. We would also recommend the ISCF Board and Challenge Programme Board consider the feasibility of expanding the Programme Board's membership to include two or three additional senior figures from industry and academia. The Programme Advisory Group would also benefit from some limited further expansion, to strengthen its expertise specifically in extreme environments, and to improve its gender diversity.

Strengthening the cross-fertilisation across strands – Interactions across strands could be further strengthened, in future iterations of the programme, through the issuing of specific calls for proposals directed exclusively to past participants or through the weighting of the evaluation criteria. A similar approach could be undertaken to facilitate cross-fertilisation across ISCF programmes. The Challenge Programme Board will however need to maintain a balance between its support for a core group of organisations and development pathways and the need to remain open to new ideas and organisations from outside the mainstream.

Improving the monitoring of the Hubs to ensure alignment with the Challenge and industry needs – We think more could be done to strengthen the mechanisms in place to make sure that RAI-EE industry is effectively driving the research agenda. Seemingly only limited due diligence was conducted at the beginning of the project to understand/verify the extent of industrial involvement. Furthermore, there seems to be no contractual basis for UKRI to request a 'change of course' should the programme management team identify the need for a fuller engagement with industry.

We recommend enhancing the current supervisory arrangements (now or in future iterations of the programme) such that industry **owns** the relevant industry-led research strategy. The ISCF RAI-EE programme board should also consider strengthen the Hub's reporting activities too (with a fuller presentation of progress and planned activities, and information to inform ISCF RAI-EE marketing and communications activities).

Lastly, we believe there would be merit in each of the Hubs developing a more extensive research strategy (with implementation plan and roadmap) that can be referred to by its own supervisory body and the Programme Board.



Appendix B

Survey analysis

The following section presents additional survey analysis to complement the analysis presented in the main body of the report.

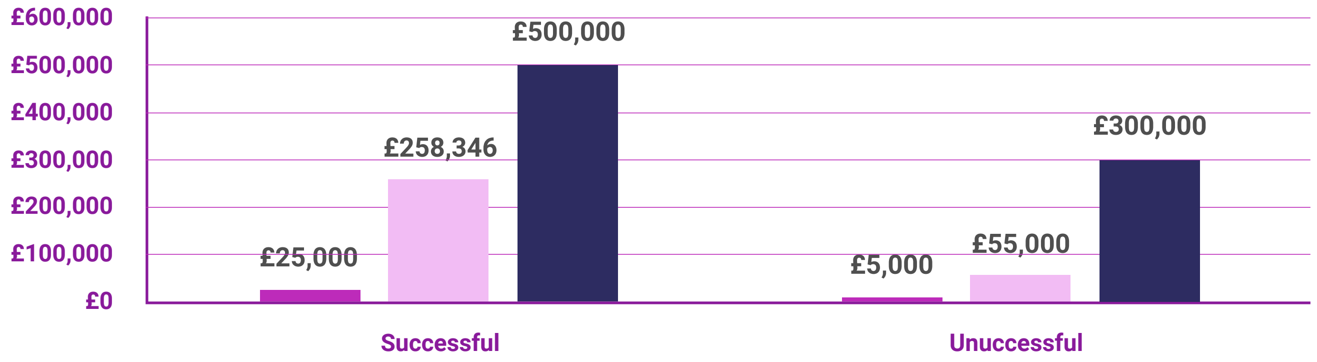
B.1 — Cumulative funding

Figure 17 – Cumulative project expenditure (median) (all three stands, businesses and academics)

Panel A: Longitudinal data - respondents where we have data across all three time points

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: CR&D and Demonstrator projects that answered this question for all three time periods. Successful n = 13 ; unsuccessful n = 5. NB. Where a respondent could not give an exact answer and gave a band, the mid-point of that band was used. Where answer to interim question was lower than figure given at baseline these figures were added together to produce interim answer, on the assumption that respondents had not appreciated that the question was cumulative.

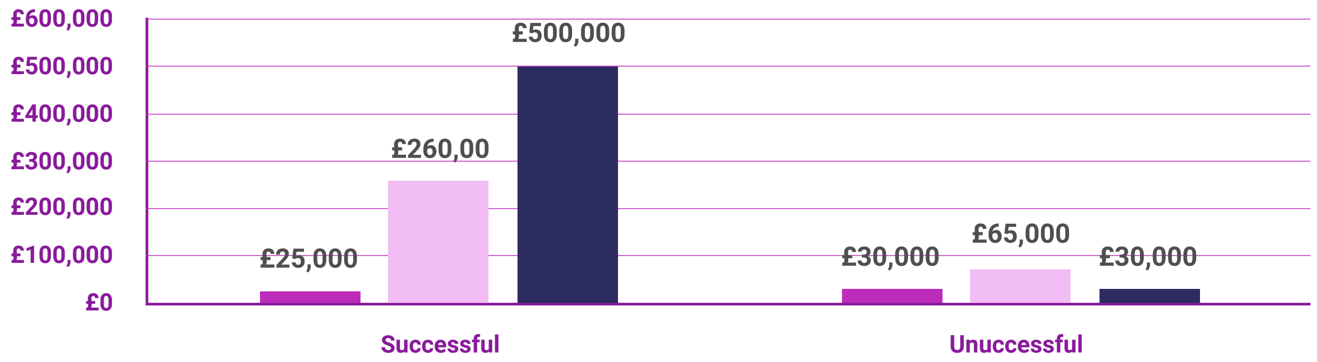
Key – Baseline Interim Final



Panel B: Longitudinal data for baseline and interim position (as reported in the Interim report) and all respondents to final survey

Base: CR&D and Demonstrator business applicants for projects in extreme environments. 60 successful and 19 unsuccessful applicants with data at both baseline and interim, plus 31 successful and 8 unsuccessful applicants from final wave. Baseline data collected from additional respondents in final wave has not been added. NB. Where a respondent could not give an exact answer and gave a band, the mid-point of that band was used. Where answer to interim question was lower than figure given at baseline these figures were added together to produce interim answer, on the assumption that respondents had not appreciated that the question was cumulative.

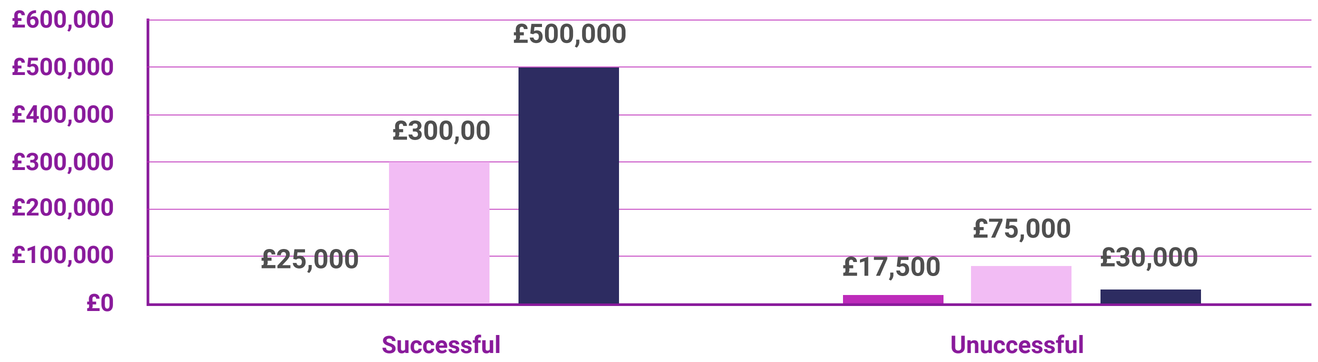
Key – Baseline Interim Final



Panel C: Cross-sectional data- all respondents in each round, baseline, interim and final surveys

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: CR&D and Demonstrator business applicants for projects in extreme environments. Successful n = 43, 46 and 31 respectively in 2018, 2019/20 and 2022/23; unsuccessful n = 16, 13 and 5 respectively. NB. Where a respondent could not give an exact answer and gave a band, the mid-point of that band was used. Where answer to interim question was lower than figure given at baseline these figures were added together to produce interim answer, on the assumption that respondents had not appreciated that the question was cumulative.

Key – Baseline Interim Final



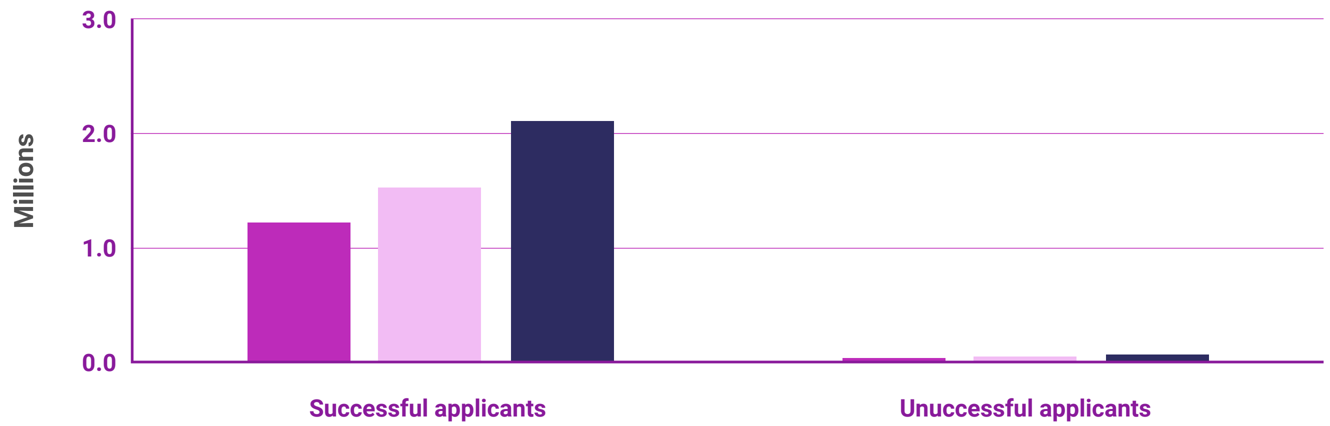
B.2 — R&D investment

Figure 18 – Average(mean) annual R&D spending on RAI in EE, £m (all three strands, both businesses and academics)

Panel A: Longitudinal data – respondents where we have data across all three time points

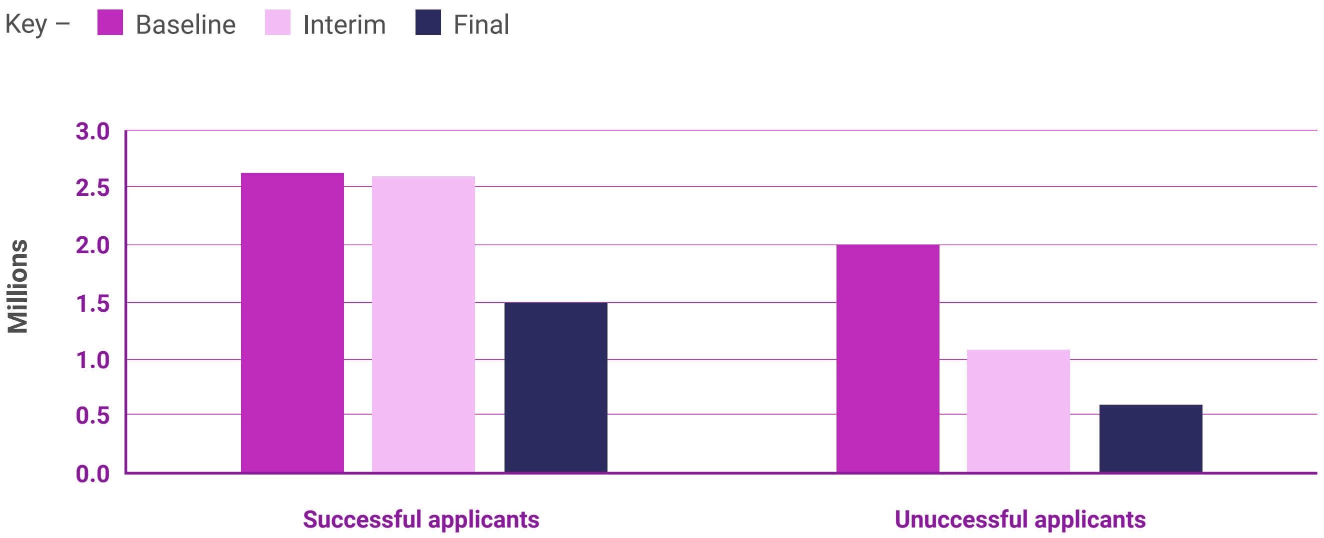
Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: 13 successful and 4 unsuccessful applicants (all three strands, both businesses and academics) with data at all three time points.

Key – Baseline Interim Final



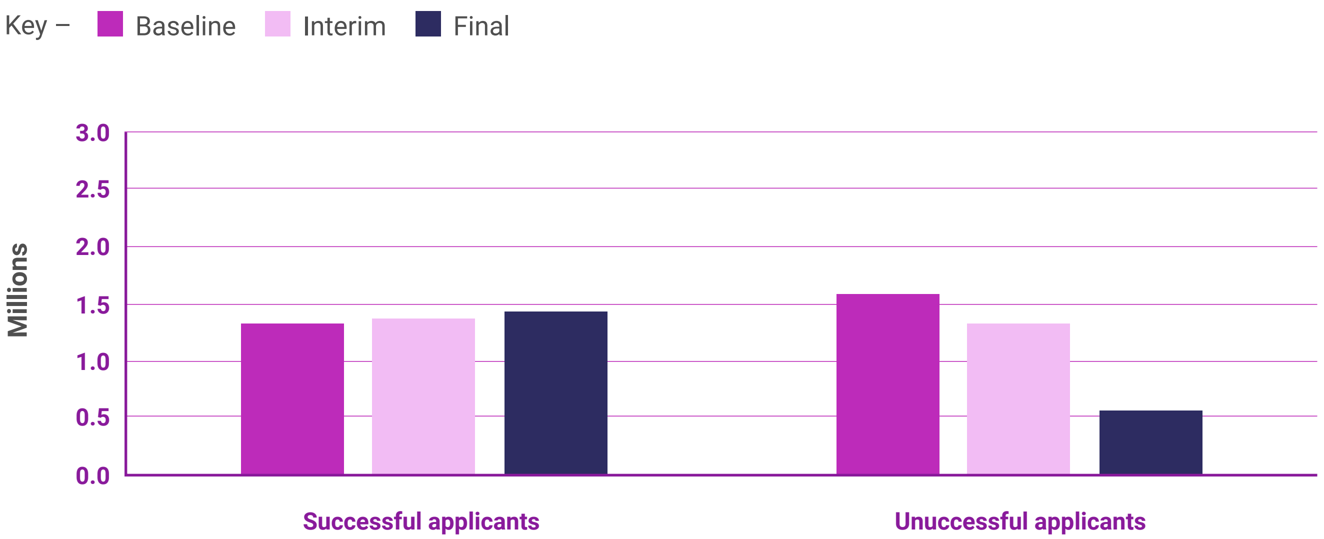
Panel B: Longitudinal data for baseline and interim position (as reported in the Interim report) and all respondents to final survey

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: Applicants for projects in extreme environments. 81 successful and 45 unsuccessful applicants with data at both baseline and interim, plus 34 successful and 13 unsuccessful applicants from final wave. Baseline data collected from additional respondents in final wave has not been added.



Panel C: Cross-sectional data- all respondents in each round, baseline, interim and final surveys

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: Business applicants for projects in extreme environments (all strands). Successful n = 56, 51 and 31 respectively in 2018, 2019/20 and 2022/23; unsuccessful n = 28, 21 and 13 respectively.

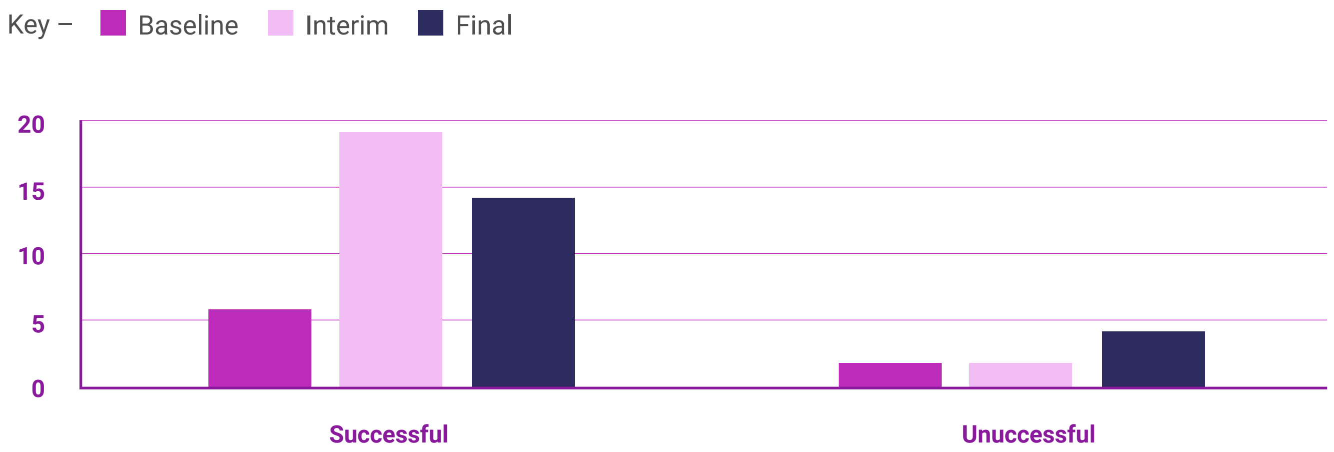


B.3 — R&D employment

Figure 19 – Average annual R&D employment in RAI-EE, mean (all three strands, both businesses and academics)

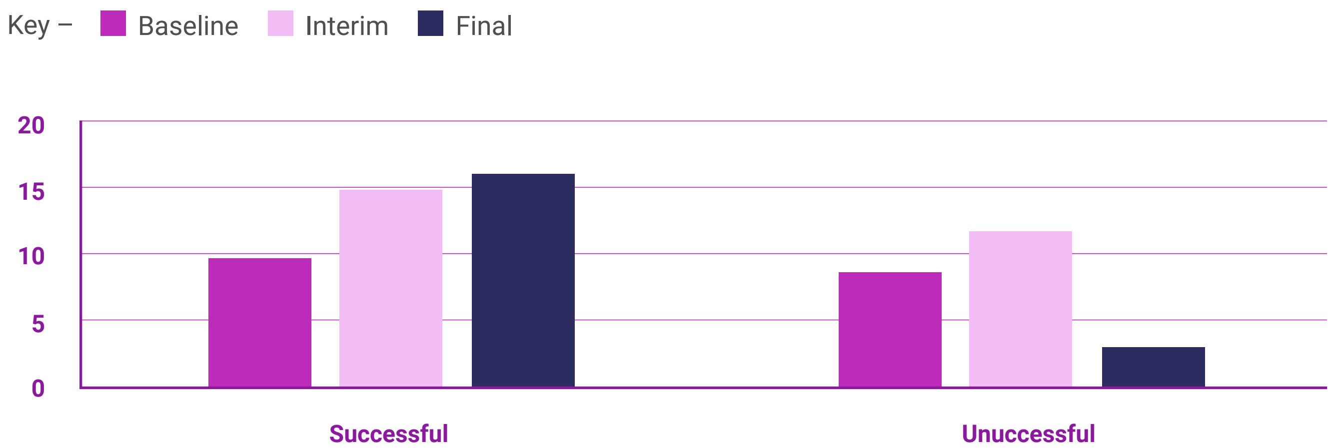
Panel A: Longitudinal data – respondents where we have data across all three time points

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: 14 successful and 4 unsuccessful applicants (all three strands, both businesses and academics) with data at all three time points.



Panel B: Longitudinal data for baseline and interim position (as reported in the Interim report) and all respondents to final survey

Source: Longitudinal survey, baseline Nov–Dec 2018; interim survey Nov 2019–Jan 2020; and final survey, Dec 2022–Feb 2023. Ipsos/Technopolis. Base: CR&D and Demonstrator business applicants for projects in extreme environments. 92 successful and 47 unsuccessful applicants with data at both baseline and interim, plus 30 successful and 13 unsuccessful applicants from final wave. Baseline data collected from additional respondents in final wave has not been added.



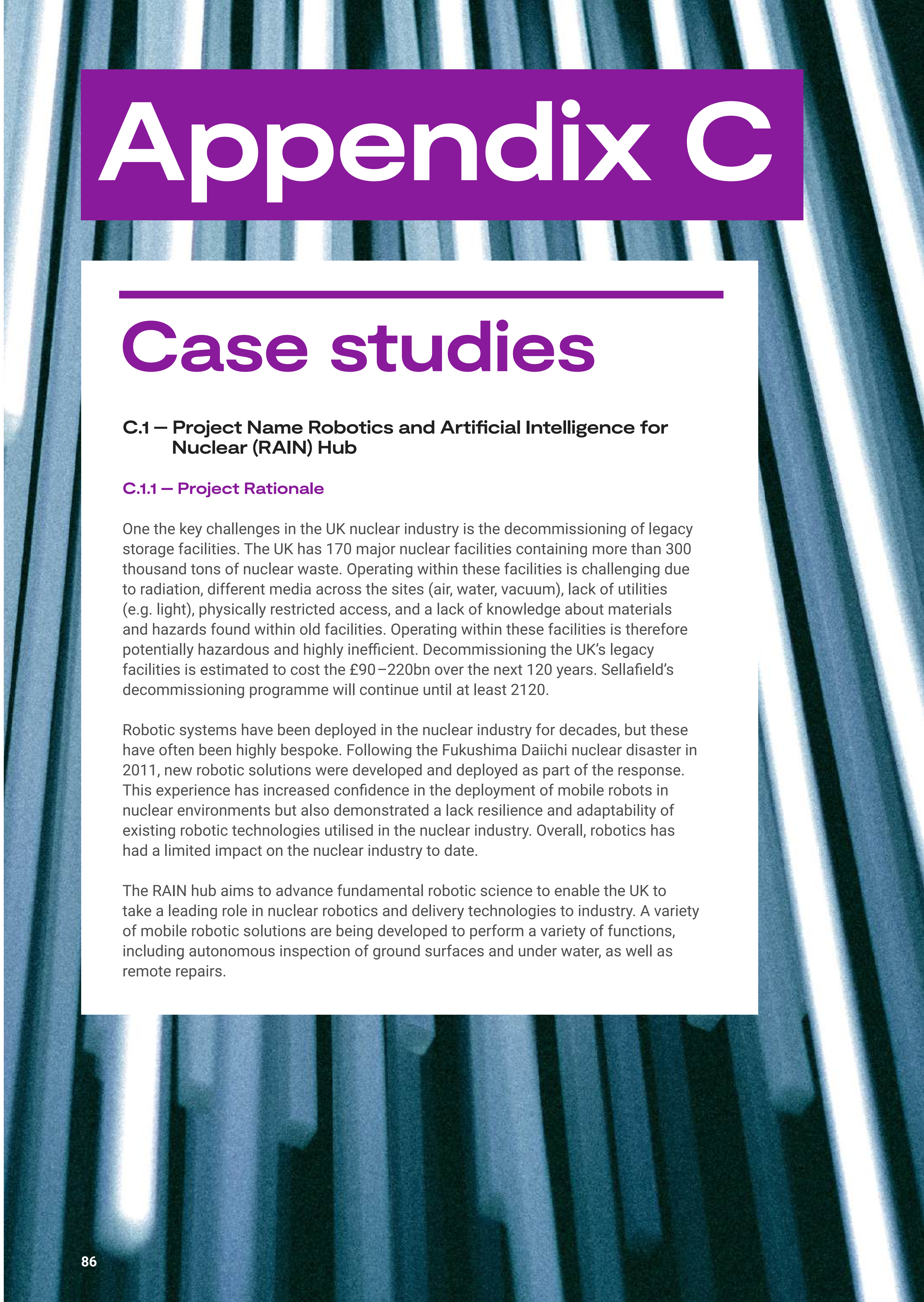
B.4 — Economic impact

Longitudinal
11 successful, 4 unsuccessful

	Successful			Unsuccessful		
	Baseline	**Interim**	**Final**	**Baseline**	**Interim**	**Final**
Turnover derived from activities relating to robotics and artificial intelligence in extreme and challenging environments *(Longitudinal data only)*	£3.5m	£5.4m	£4.7m	£0.005m	£0.4m	£0.05m
Exports (as % of turnover derived from activities relating to robotics and artificial intelligence in extreme and challenging environments)	20%	38%	25%	0%	20%	35%

Cross-sectional
50/48/34 successful, 28/22/13 unsuccessful

	Successful			Unsuccessful		
	Baseline	**Interim**	**Final**	**Baseline**	**Interim**	**Final**
Turnover derived from activities relating to robotics and artificial intelligence in extreme and challenging environments *(Longitudinal data only)*	£3.0m	£4.2m	£2.7m	£2.8m	£4.7m	£2.3m
Exports (as % of turnover derived from activities relating to robotics and artificial intelligence in extreme and challenging environments)	11%	23%	21%	7%	22%	32%



Appendix C

Case studies

C.1 — Project Name Robotics and Artificial Intelligence for Nuclear (RAIN) Hub

C.1.1 — Project Rationale

One the key challenges in the UK nuclear industry is the decommissioning of legacy storage facilities. The UK has 170 major nuclear facilities containing more than 300 thousand tons of nuclear waste. Operating within these facilities is challenging due to radiation, different media across the sites (air, water, vacuum), lack of utilities (e.g. light), physically restricted access, and a lack of knowledge about materials and hazards found within old facilities. Operating within these facilities is therefore potentially hazardous and highly inefficient. Decommissioning the UK's legacy facilities is estimated to cost the £90–220bn over the next 120 years. Sellafield's decommissioning programme will continue until at least 2120.

Robotic systems have been deployed in the nuclear industry for decades, but these have often been highly bespoke. Following the Fukushima Daiichi nuclear disaster in 2011, new robotic solutions were developed and deployed as part of the response. This experience has increased confidence in the deployment of mobile robots in nuclear environments but also demonstrated a lack resilience and adaptability of existing robotic technologies utilised in the nuclear industry. Overall, robotics has had a limited impact on the nuclear industry to date.

The RAIN hub aims to advance fundamental robotic science to enable the UK to take a leading role in nuclear robotics and delivery technologies to industry. A variety of mobile robotic solutions are being developed to perform a variety of functions, including autonomous inspection of ground surfaces and under water, as well as remote repairs.

C.1.2 — Project overview

The founding partners of the RAIN hub include seven leading universities – University of Manchester, University of Oxford, University of Bristol, University of Liverpool, University of Sheffield, University of Nottingham, Lancaster University – and the UK Atomic Energy Authority's (UKAEA) Remote Applications in Challenging Environments centre (RACE). Since the proposal stage, the University of Leeds, University of Reading and the University of Newcastle has joined hub. The expertise represented in the hub include departments of Electrical and Electronic Engineering, Mechanical, Aerospace and Civil Engineering and Computer Science.

The RAIN hub is closely aligned with existing investments such as the £4.6m Robotics for Nuclear Environment programme led by the University of Manchester and funded by the EPSRC since 2017. RAIN investigators are also closely involved in national networks such as Innovation UK's Robotics and Autonomous Systems (RAS) Special Interest Group, the UK RAS Network (under EPSRC) and others.

The hub aims to deliver "the necessary step changes in fundamental robotics science and establish the pathways to impact that will enable the creation of a responsible research and innovation infrastructure that has the capability to lead the world in nuclear robotics and deliver technology to industries operating in many other extreme environments."

The Continuous Autonomous Radiation Monitoring Assistance (CARMA) is one of several technologies being developed to address the specific challenge of improving radiological monitoring of large floor areas. Developed in collaboration with Sellafield, it maps and continuously inspects floor space for radioactive contamination. It primarily aims to replace routine inspection and is not designed to be deployed in environments with high gamma-radiation.

C.1.3 — Key outputs, outcomes and impacts

In parallel with the effort to commercialise the CARMA 1 and 2 robots, researchers within the hub are working to further develop the platform and potentially arrive at a CARMA 3.0. One avenue of interest to both the university and to Nuvia is the development the capability to be deployed outdoors in open spaces, replacing Nuvia's current 'Ground Hog' platform.

The extensive work with Sellafield has led to them appointing a Head of Robotics and the establishment of RAICo – a collaborative robotics and AI facility in Cumbria, that links Sellafield, the Nuclear Decommissioning Authority and members of RAIN with the aim of delivering new robotics technology on to the Sellafield site. Dounreay Site Restoration Ltd: The Vega robot has been deployed into an active waste store on the Dounreay site and in 2021 and 2022 was deployed into an active drain, which requires urgent characterisation to allow the decommissioning of laboratory facilities to continue.

More broadly, the deployment of CARMA and subsequent platforms at the Sellafield site can help make the deployment of autonomous robotic systems more widespread at Sellafield and in the nuclear industry. Robotic solutions such as CARMA are also seen as essential for progress towards the targets in the Nuclear Sector Deal negotiated with the government.

Beyond CARMA, as of Jan 2022; RAIN has supported over 35 industrial projects (including over 15 SME projects), 16 secondments into industry and academia, and published over 250 journal articles. RAIN has supported the nuclear research community via five Working Groups (Remote Handling, Remote Inspection, Autonomy & Verification, Human Robot Interaction and Standardisation). From a research perspective, the work in RAIN has led to the development of a remote inspection technologies, linking platform development, sensing and mission planning that have enabled inspection equipment that can be deployed to autonomously survey nuclear environments. In addition, multiple technologies have been developed that allow glove boxes to be operated remotely, eliminating the need for people to be exposed to these high-risk environments.

From the robotic-human and human-robotic interaction and RI groups the Hub has undertaken deployments in over 40 simulated (physical and digital) environments and active deployments in 5 environments. Four products are being commercialised. Via the A&V group, they have fostered connections with the ONR on the topic of RAI adoption in the nuclear industry. Their work in standardisation has begun to set the foundations for improved interoperability from human and machine perspectives. RAIN has hosted a regular webinar event series showcasing progress during the pandemic. Events such as these have helped to foster enthusiasm and support from the network of over 350 industrial representatives and over 100 businesses that RAIN is proud to call its fanbase.

C.1.4 — Technology spotlight

The case study describes the route to commercialisation of the Continuous Autonomous Radiation Monitoring Assistance (CARMA), one of several platforms developed by RAIN. The hub has engaged with industry partners, including Nuvia Ltd.

Its development started in 2016 and was initially supported by a post-doctoral research award funded by the University of Manchester, Sellafield and the National Nuclear Laboratory (NNL). This developed the platform to TRL 3–4. The second generation of the platform, 'CARMA 2' is under development within the hub in close collaboration with Sellafield, the intended end user. This further developed the platform approximately to TRL 7.

CARMA aims to address the specific challenge of improving radiological monitoring of large floor areas. CARMA was successfully deployed on two occasions in operational facilities at the Sellafield site, within the Thermal Oxide Reprocessing Plant (THORP) in Cumbria. The facilities both contained a known, non-hazardous α contamination, and the test served to test CARMA's ability to autonomously detect a contamination source and generate a geometric and radiometric map of the area.

The CARMA platform is being developed for commercial use by Nuvia Limited, supported by a 2-year Knowledge Transfer Partnership (KTP) project, part funded by Innovate UK. Nuvia expected CARMA to be ready for market by the 3rd quarter of 2020 (but it is unclear whether this has been achieved). It will then be deployed as part of Nuvia's service contracts and possibly sold separately as hardware, hoping to achieve multi-million-pound sales within the UK and abroad, including in Canada, the US and Japan. In addition, the CARMA project has supported the development of skills within Nuvia and informed their R&D strategy going forward.

For Sellafield and other end-users, CARMA would primarily be deployed to perform routine inspections, replacing the current practice of deploying health-physics surveyors to do manual readings. This will help reduce risk of radiation for protection personnel and free up their time to perform more complex tasks, as well as reduce cost and improve data quality. More widely, the deployment of CARMA marks a milestone in the use of autonomous robotics in the nuclear sector in the UK and has already helped pave the way for the deployment of other autonomous robotic systems at Sellafield and in the nuclear industry.

Key challenges in the development of the CARMA platform have been the collaboration between the research hub, the end user, Sellafield, and the commercial supplier, Nuvia. Due to some disagreement about priorities the initial CARMA platform was not commercialised, but CAMRA 2 and CARMA 3.0 are under development by Nuvia and are currently undergoing testing.

C.2 — National Centre for Nuclear Robotics (NCNR) Hub

C.2.1 — Project rationale

Nuclear facilities require a wide variety of robotics capabilities, engendering a variety of challenges for robotics and AI due to the complex and dangerous environments. These challenges are presented across the lifecycle of nuclear power stations, from newbuild through to decommissioning, and handling nuclear waste. Nuclear waste is one of the biggest environmental remediation challenges in Europe, the UK alone contains nearly 5m[19] tonnes of legacy nuclear waste.

In high gamma environments, human entries are not possible at all. In alpha-contaminated environments, air-fed suited human entries are possible, but engender significant secondary waste (contaminated suits), and reduced worker capability. Eliminating the need for humans to enter such hazardous environments wherever technologically possible is a pressing need.

The nuclear industry is high consequence, safety critical and conservative. It is therefore critically important to rigorously evaluate how well human operators can control remote technology to safely and efficiently perform the tasks that industry requires.

A key focus of the NCNR Hub is robotics for nuclear decommissioning, however their work also encompassed robotics for in-service inspection and maintenance and Plant Life Extension (PLEX) for live nuclear plans and operations in new-build power stations.

[19] University of Birmingham. 'The Challenge'

C.2.2 — Project overview

The Hub was originally led by the University of Birmingham in collaboration with 7 university partners, and then expanded to include a further 3 university partners.[20] The Hub comprised of co-PIs/coinvestigators – Queen Mary University of London, Lancaster University, the Royal Institution of Great Britain and the Universities of Essex, West of England, Edinburgh, Leeds, Lincoln, Bristol, Plymouth and Southampton.

NCNR was launched in November 2017 through ISCF-RAI. Since February 2021, when an accident damaged a reactor fuel element without impacting public health and safety, the facility has been safely shut down. But, as of March 10th, the Nuclear Regulatory Commission determined that the National Institute of Standards and Technology met the standards to safely restart the NIST research reactor in Gaithersburg, Maryland, and therefore NCNR operations have resumed. The Hub is supported by an estimated £41m[21] over three years, including £12.3m from the ISCF RAI programme, further funding from the research institutes involved and private investors.

In addition to the core partners, the NCNR Hub is supported by 30+ partners from several stakeholder groups across the value-chain. While a variety of organisations committed to supporting the Hub at application, this has expanded over time, with a number of organisations joining the Hub since its establishment (some of which are included in the following table). One of the NCNR partners, Shield Investment Management, is a specialised RAI venture capital fund particularly in under-roboticised industries. Shield have ring-fenced £10m capital to run alongside all NCNR Hub research, to fund spin-out companies and industrialisation of Hub IP.

The key research activities for the NCNR hub are summarised and grouped around the following themes:

- Characterisation: detecting and labelling radiation levels, waste materials and contaminants, and determining other parameters (e.g., thermal and chemical), 3D modelling scenes.
- Waste handling: Developing robots to carry out complex tasks to sort, store or dispose of radioactive material remotely.
- Cell decommissioning: Developing robots to dismantle radiation environments (e.g., contaminated pipes, vessels and steelwork).
- Underwater interventions: Developing robots to access, inspect and map complex underwater nuclear sites.
- UAV based site monitoring: Developing unmanned aerial vehicles (i.e., drones) to detect radiation levels both during routine monitoring and after emergencies.

C.2.3 — Key outputs, outcomes and impacts

The Hub is on target for where the partners had hoped to be at this stage in time. A wide array of projects has advanced since the inception of the NCNR. The NCNR has been particularly prolific in supporting research in the UK and international collaborations. Overall, the NCNR has supported the production of 400 peer reviewed publications, with nearly 700 total articles referencing and making use of NCNR work. In addition, the research being done has supported the creation of new products and services with two SBRI projects funded by Innovate UK brining products to market.

In particular, Bristol Robotics Laboratory are now working more closely with end users in the development of the software interface that mediates the human-robot interaction. Collaboration with end-users at this stage of development is vital to ensure uptake of the solution, as the interface needs to reflect the needs and actions of the anticipated operators.

Another example is the work conducted by Professor Tom Scott, University of Bristol, in mapping of complex environments. Professor Scott and his team have developed technologies to carry out autonomous aerial radiation surveys which have been carried out at the Fukashima disaster site, the Chenobyl disaster site and the Pridniprovskiy Chemical Plant (PChP) site in Ukraine, a heavily contaminated uranium ore processing site. By characterizing where the hazards lie across a contaminated site, organisations involved in nuclear clear-up are better able to understand the needs, risks and opportunities for future clean-up work. This also has implications for the efficiency and effectiveness of future programmes and policies, including build programmes such as Chernobyl solar farm.

Pre-existing relationships between the participating research groups, NNL and Sellafield, enabled by previous and parallel projects, was mentioned by interviewees as a success factor.

[20] Joined NCNR via the Flexible Partnership Fund
[21] Based on NCNR grant application

Project partners also noted the benefit of being supported by a programme with specific objectives to support industry engagement. The overarching objective of the Research Hubs and NCNR to support industry led research has encouraged and supported the participating research groups to focus on translational work. This translational aspect was thought to be a good complement to other funded work focussed on more fundamental/lower TRL technologies.

To highlight the tension between researchers' priorities and ways of working, research partners highlighted that structure of NCNR work programmes support iterative development of solutions in collaboration with end-users, in comparison with industry led innovation projects which were sometimes subject to stricter timelines and more targeted development. By contrast, the NCNR Hub was enabling research groups more opportunities to engage in collaborative development with other research groups, exploring a wider scope of options and opportunities for leveraging knowledge and resources.

C.2.4 — Technology spotlight

One example of the NCNR work in cell decommissioning is the integration of two parallel NCNR projects. The first project, the development of an algorithm to deliver intelligent path planning for cutting radioactive materials (University of Birmingham) has been demonstrated at the NNL test-rig in line with requisite regulations. This algorithm is now being adapted for application on the second project, the further development of a mobile robot platform for cutting and gasping (Bristol Robotics Laboratory). The integration and adaption of this algorithm has resulted in a publication, with a second expected in the future.[22]

Future planned work for the development of this mobile robot platform includes further development of the cross-cutting algorithm to better exploit the degrees of freedom enabled by the mobile base, integration of a third parallel NCNR project focused on developing software for robotic grasping and further collaboration with Sellafield in the development of the human-robot interface for teleoperation. The mobile platform has been demonstrated within test environments, and research partners are planning more demonstrations in future as the system increases TRL.

Cutting and dismantling in safety-critical environmental are often too complex or slow to

perform remotely. As such, this work could limit the involvement of humans in the cutting and sorting of nuclear waste and reduce exposure risk. Furthermore, automation of aspects teleoperation of reduces the cognitive load on operators and improves efficiency and cost-effectiveness of operation.

Research partners felt the structure of NCNR work programmes better supported iterative development of solutions in collaboration with end-users and across different research groups. The success of these projects in part leverages pre-existing relationships between the participating research groups, NNL and Sellafield enabled by previous and parallel SBRI and EPSRC funded projects,[23] allowing NCNR to further aggregate and mobilise such relationships and knowledge as presented here.

C.3 — FAIR-Space

C.3.1 — Project rationale

Advances in robotics and autonomous systems will play a major role in human and robotic space missions. These technologies can greatly assist space exploration by humans, as well as enabling exploration of space "by proxy". Robots assisted by AI technologies will have a key role in deploying infrastructure in preparation for human arrival, assisting crews in space and managing assets left behind from exploration missions. They will progressively take over support and repetitive functions, allowing humans to focus on tasks that require a higher level of judgement. Robotic spacecraft are also key for deep-space no-return missions and for venturing into environments hostile to humans.

[22] Pardi, T., Ortenzi, V., Pipe, T., Ghalamzan, A. M., and Stolkin, R. (2019) **Maximally manipulable vision-based motion planning for robotic rough-cutting on arbitrarily shaped surfaces**

[23] SBRI project, 'Integrated robotic system for characterisation and decommissioning', 971566 and EPSRC Programme Grant, Robotics for Nuclear Environment, EP/P01366X/1

The National Hub of research excellence on future AI & robotics for space (FAIR-Space) was set up in November 2017 to address UK priorities in orbital manipulators, autonomous planetary vehicles, and robotic support for manned exploration. The overall aims of the Hub were to develop the UK space robotics community, increasing its international profile, and to contribute actively to the goal of creating a £40bn UK space industry by 2030, which was set out in the Government's Space Innovation and Growth Strategy. The Hub stands out from prior research in its focus on increasing the capabilities of space robots to perform more complex and long duration tasks, with independence and autonomy from ground crew.

C.3.2 — Project overview

FAIR-Space was led by the University of Surrey and comprised over 30 UK and international partners. Five other UK Universities participated in the hub: these were Imperial College London, the University of Edinburgh, the University of Liverpool, the University of Salford and the University of Warwick.

Surrey has a long tradition of research in space and satellites. As home to the Surrey Space Centre, the University has contributed to UK space engineering research since the 1970s, and pioneered development and launch of the world's first university-led micro and nano spacecraft. Since then Surrey has continued to work on space research and real-world demonstrators. For example, the first in-orbit robotic space debris removal demonstrator mission ('RemoveDebris') and Surrey's STAR-Lab has contributed to national and international missions such as MoonLITE, Moonraker, Proba3, ExoMars and Chang'E-3.

The FAIR-Space Hub aimed to go beyond the current state of the art in areas such as robotic sensing, mobility, manipulation, autonomous capabilities, and robot-human interactions with the goal of enabling space robots to perform more complex and long-term missions in space, reducing their dependence on ground crew and additional infrastructure. Autonomous space robots can take many forms and target a range of applications. The 5 research areas where FAIR-Space focuses are:

- **Vision & Perception** – focused on the develop of sensors and systems for autonomous navigation and manipulation of satellites.
- **Mobility and Mechanisms** – developed new cost-effective mobility and propulsion systems to handle variations in orbit or surface circumstances.
- **AI & Autonomy** – requires the development of low latency and resource efficient systems that can gather information, analyse it, and accurately implement the required solution.
- **Astronaut-robot interaction** – new human space systems are necessary to support the successful interaction between humans and robots in zero g or on a planetary body.
- **System Engineering** – supports the development of new software engineering solutions for reliable, secure, and resilient autonomous robotics in space.

The Hub was launched in November 2017 through ISCF-RAI, with a duration of 3 years, and a £7.95m research grant from UKRI and the UK Space Agency (UKSA). This funding has attracted a further £7.5m fund from the private sector and an additional £15m business development fund.

C.3.3 — Key outputs, outcomes and impacts

In terms of the Hub overall, FAIR-Space experienced difficulties in the first few years in operations. The Hub's project manager was off sick with major illness and there was no replacement put in place. This had a negative impact on the engagement with industry and the identification and development of use cases. There was a baseline of activity of specific partners presenting in workshops and liaising with industry but not a strong connection back to the development of specific use cases. Partners had been doing good research and researchers were using the Hub to develop their research activities further that progressed well across the five themes of the Hub. The lack of progress against early goals precipitated a change of Hub management and this somewhat negative assessment in terms of industry engagement did improve with the appointment of Prof. Sir Martin Sweeting as new Hub director in July 2019.

The Hub was then able to build new relationships with industry partners and support research of interest to the wider space community. However, the cycles upon which research and industry operate are generally misaligned; researchers who are affiliated with academia are dependent on the funding processes of public and private organisations, which are often cumbersome due to the necessary due diligence. Industry, on the other hand, operates in a highly competitive, time-sensitive environment in which the winner is the first player to reach the necessary margins for profitability. The benefits of collaboration between the developers and the end-users of new technology are clear, but meaningful collaboration remains a challenge so long as the issue of time horizons persists. In the space sector, where development cycles are particularly long, the challenge is even greater.

Despite the headwinds that the Hub experienced, additional resources were provided by Surrey to the new Director so that activity became more focussed and was able to accelerate developments across the five thematic research areas. Academics working in each of the areas published high quality research in support of technological advances, however it does not appear that the majority of these have yet found commercial application.

Given this context, the FAIR-Space Hub focussed primarily on creating awareness of the potential for R&AI to exploit space, with the aim of increasing the awareness and appetite for industry and public organisations to invest in the sector and drive demand. The Hub undertook cutting-edge academic research both in its own right and in collaboration with well-known players in the space sector such as NASA. It participated in a series of cross-thematic international events such as the IEEE International Conference on Robotics and Automation (ICRA 2021), where showcased the Hub's research and participated in discussions of standards, regulatory issues, remote asset protection and cybersecurity. Due in part to the FAIR-Space activity, the Royal Society asked the Hub Director to lead its 'perspective' discussions on the implications of the space sector on HMG and society in 2075, within which space robotics and autonomous systems are a key sector. The work of the Hub also laid a foundation of standards for an emerging sector, which will simplify future development cycles and possibly bring them in line with those typically required within industry.

C.3.4 — Technology spotlight

The FAIR-SPACE Hub is the ISCF RAI Research Hub focussed on the development of robotics for space technologies to address UK priorities in orbital manipulators, autonomous planetary vehicles, and robotic support for manned exploration. FAIR-Space comprises over 30 partners, including six UK universities, specialist space industry players, large corporates, and international organisations such as NASA, ESA and China Aerospace Science and Technology Corporation. The Hub is supported by £7.95m research grant from UKRI and the UK Space Agency (UKSA), a further £7.5m fund from the private sector and an additional £15m business development fund.

The most prevalent effect of the Hub to date is an increased volume of excellent research on RAI, and the aggregation and identification of RAI in space research by the wider space sector. The Hub has been active in engaging with events around the country and internationally, with other ISCF RAI funded Use-inspired Research Hubs and is engaged with international standards committees.

After some initial teething issues, the Hub's industry links has been less strong than anticipated, especially with the space sector. However following changes to management, hub leadership is rebuilding and fostering new industry links to regain momentum.

One illustrative example of the FAIR-Space Hub's work is a ground-based robotic demonstrator that has been designed and implemented to simulate in-orbit manipulation of space targets. This allows simulating, studying and further developing three different space applications:

- In-orbit satellite servicing.
- In-orbit telescope assembly.
- Active debris removal.

The demonstrator brings together industrial (including Shadow Robot Company) and academic partners as well as different technologies relevant to the Hub (e.g. sensing & perception, robotics grasping and manipulation, AI and developments in computer vision/perception). This demonstrator provides a facility for UK industry to develop and test in-orbit satellite assembly and servicing capabilities.

Shadow Robot used elements of the demonstrator's software in combination with their existing robot hand technology to develop an autonomous orbital robot to grasp the engine nozzle of a satellite. This technology was then piloted and showcased on the demonstrator. This project is the first collaborative R&D project Shadow Robot has delivered with partners in the space sector, and thanks to its success the company is now establishing space as another one of their target emerging markets.

Potential societal and economic impacts are, at this point in time, rather speculative and can only be stated at a qualitative level, however the demonstrator could be used by companies in the area of remote teleoperation and telepresence as well as other sectors including manufacturing, Agri-tech, construction and pharmaceuticals.

C.4 — UK Robotics and Artificial Intelligence Hub for Offshore Energy Asset Integrity Management (ORCA)

C.4.1 — Project rationale

The international offshore industry is expanding, but faces a number of challenges, including low oil prices, decommission of ageing infrastructure, small margins on the production of renewable energy as well as an ageing workforce. Offshore robotics has the potential to address these industry challenges, but this requires advancement in several areas of interdisciplinary research. One challenge relates to the interface between human operators and autonomous systems, and a joint project with multinational oil and gas company Total illustrates how the ORCA hub works with industry to address this challenge.

The offshore industry, including the oil and gas sector and the renewables sector, in is worth £90bn per year. However, the international offshore industry faces a number of challenges, including low oil prices, decommission of ageing infrastructure, small margins on the production of renewable energy as well as an ageing workforce.

Offshore robotics has the potential to address these industry challenges but, in turn, face a series of interdisciplinary research challenges:

- Asset Integrity Management requires the surveying of and the placement of non-destructive evaluation sensors onto complex structures in the dynamic and challenging off-shore environment.
- Offshore robotic asset management and self-certification requires systematic information gathering through proactive and reactive sensor deployment.
- There is a communication barrier between the robots and the operator, particularly in remote highly challenging, hazardous environments with multiple vehicles or platforms. The resultant lack of transparency can result in reduced trust and situation awareness and hinder true human-machine teaming, resulting in unnecessary aborts or effortful manual manipulation of the assets.
- Inspection for certification in offshore environments is often labour intensive, risky and expensive. A major obstacle for adopting RAI for certification is the need to assure systems in terms of their safe operation. Current regulatory frameworks do not effectively address the technologies used in RAI systems.

The ORCA hub ('Offshore Robotics for Certification of Assets) was established to address these research challenges, and aims to radically change way offshore structures are inspected repaired and maintained to enable these cheaper, safer and more efficient working practices.

C.4.2 — Project overview

With the investment from the ISCF RAI programme, the hub aimed to "develop technologies that enable reliable, robust and certifiable robot assisted asset inspection, autonomous decision making and intervention capabilities for the off-shore domain, with specific focus on challenges inherent to this extreme, unpredictable environment".

- Mapping and surveying of complex structures using multiple robots equipped with distributed, mobile optical and acoustic spatial sensors and industry accepted non-destructive evaluation (NDE) sensors in the dynamic and challenging off-shore environment.
- Planning and execution of efficient, localisable and repeatable navigation and interaction of heterogeneous robotic deployment platforms (wheeled and legged for topside, aerial, marine) for sensor placement and manipulation in extreme and dynamic conditions – with specific emphasis on failure prediction, re-planning and recovery strategies.
- Human machine teaming through effective communication of world view, system actions and plan failures between remote robot and operator to develop trust and avoid unnecessary aborts.
- Designing robotic systems that can self-certify and guarantee their safe operation including when learning systems are included, predicting, and diagnosing faults.

C.4.3 — Key outputs, outcomes and impacts

Ultimately, ORCA managed to achieve success in producing high quality research in each of the key work packages as laid out in their long term plan. Across all projects the hub was able to generate more than 260 papers across its funding period with contributions from more than 100 individual researchers.

Engagement with Industry was a key barrier to the long-term success of the hub. Early on, even going back to the development of the hub proposal, industry was never clear on what best to invest in. There was a distinct disconnect between low-TRL research and industry needs, where there must be a strong alignment between the research and a potential business case. This meant that the hub was forced invest more time than initially planned to get industry partners on board limiting the outputs of the hub overall, but also of individual research projects.

Despite the early difficulties, the hub was ultimately able to establish collaborations with 24 industry partners. Most of these collaborations were with larger firms, who could conceivably continue the research after the funding for ORCA concluded. The 3-year timeline was a key obstacle for SME engagement, as most research required additional time, that most SME's would have difficulty sustaining that level of R&D funding. For the industry partners that did engage, they managed to produce two patent applications, complete more than 10 field trials, establish 1 spinout with three more in preparation.

C.4.4 — Technology spotlight

The hub focussed on a number of 'technology spotlights', including MIRIAM (Multimodal Intelligent inteRation for Autonomous systeMs). MIRIAM is a 'chatbot', enables operators to interrogate autonomous underwater vehicle's actions and status in real time through natural language chat.[24] It was initially developed with grant support from the Defence Science and Technology Laboratory (DSTL) and addresses one of ORCA's key research challenges of improving the human-robot interface and increasing transparency between the operator and autonomous system.

Total has been involved in ORCA hub since the pre-award workshop, is represented on ORCA's Industry Leadership Panel (ILOP) and took part in ORCA demonstration events during 2018 and 2019, where MIRIAM and other technologies were showcased. Total identified MIRIAM as relevant to their robotics programme and in late 2019, a joint industry project with Total was one of several joint industry projects established.

The collaboration feeds into Total's ongoing project, 'JARVIS', which aims to allow human operators to communicate with the vehicle or system and create effective teaming strategies between the autonomous systems. The collaborative project is still relatively new, but on 21st January, Total launched a pilot at their Shetland gas plants, which features contributions from OCRA. A researcher from the ORCA team has travelled to the plant to provide support. If the pilot is successful, the technology might ultimately be commercialised through a spinout.

Key benefits of the new technology to the oil and gas industry include reduced operator error with help from the improved natural-language user interface, and cost-reduction resulting from fewer personnel needed on offshore platforms and reduced time needed to complete activities. Longer term, the collaborative project is part of an effort to transform the North Sea basin as oil and gas is phased out and new floating wind farms can be designed for autonomous inspection and operations.

The benefit to the UK of projects such as MIRIAM/JARVIS is the additional investment it attracts which has materialised in a multinational company (Total) choosing to invest a large proportion of its R&D in the UK, as the country is seen as a technology leader. Programmes such as ISCF-RAI is seen to support this position and ensure future investment.

[24] Hastie, H., Garcia, F.J.C., Robb, D.A., Patron, P., Laskov, A. (2017), '**MIRIAM: A Multimodal Chat-based Interface for Autonomous Systems**', Heriot Watt University.

C.5 — Autonomous Robotic InSpEction (ARISE)

C.5.1 — Project rationale

The modern world needs sophisticated mineral products which increasingly need to be mined underground as surface deposits are depleted. Extraction relies on blast mining processes which require detailed geotechnical inspections to be undertaken post-blast to ensure safety before mining operations can proceed. The post-blast environment is dangerous, with risk of rock falls and fumes endangering human inspectors. Safety protocols in the mining industry also vary globally with the risk to inspectors increasing in some areas.

The aims of this project were to apply robotics technologies developed for rovers in the space sector to undertake post-blast mine inspections, creating an inspection robot to undertake autonomous surveys of geotechnical conditions during the period immediately after the blast. This would reduce the risk to human inspectors and allow safety inspections to be taken sooner, thus increasing efficiency.

C.5.2 — Project overview

The project was led by GMV Nsl Limited (GMV), working with Sundance Multiprocessor Technology Ltd, Archangel Imaging and the University of Exeter. It built on GMV's core business in the space sector, and aimed to adapt their existing autonomy software and mapping capabilities.

There were three focus areas for the research and development work: testing FGPA (Field Programmable Gate Array) electronics for navigation and mapping, transitioning algorithms used in space for this environment; adding artificial illumination to adapt the robot; and testing the use of LIDAR for mapping. Following design work, the project was intended to include shakedown testing in Ministry of Defence bunkers, two field deployments in Cornwall, and final full-system, end-to-end field testing in different mining environments. However, COVID meant that some field deployments were substituted with testing in simulated environments.

C.5.3 — Key outputs, outcomes and impacts

The key objectives of the project were achieved but as the early stages of the project took place during COVID-19 restrictions, some of the proposed work was adapted. The original proposal had been to attach software components directly to the robot, whereas what was produced is a standalone instrument which can either be used as a handheld device or bolted on to any robot system. Further developments included a new electronics board facilitating the interaction of the FGPA with the robotic components.

Early results from field testing in 2021 were presented at the **TAROS Conference 2021**. At that time 400GB of 3D mapping data had been collected which was crucial to understanding the performance of the system. Overall data quality was considered high, including capturing failure cases which could be addressed for further development.

The original aspiration for the project, to commercialise the development in a mining environment, has not yet been achieved: the reduced ability to carry out field tests resulted in meaning less opportunity to fully analyse performance in a live mining scenario, and to demonstrate that the solution works to potential commercial collaborators and customers. However, the majority of planned outputs were completed.

The instrument created is now being applied in further GMV projects and Innovate UK developments by other UK entities. It has allowed GMV to apply for additional funding and work including with the European Space Agency and UK Space Agency. Sundance's work on the project enabled them to design a flexible platform allowing for simple addition of new modules and sensors to a flipper robot: this robot has a range of potential uses including building inspection and mineshaft mapping.

C.6 — AutoNaut for extreme environments

C.6.1 — Project rationale

Autonomous boats play an increasingly important role in collecting a wealth of research data to monitor weather patterns, climate change, the state of our oceans and the aquatic life within them. Much of this data would otherwise be difficult to collect due to the cost, challenging conditions, and long duration of the data collection. The use of autonomous vessels in air–sea interaction studies allows for measurements very close to the water surface, with minimal disturbance to the surrounding air and water parcels. Other advantages include:

- The ability to launch and recover the vessels from the shore, cutting down costs and reliance on ship time for study; the lack of emissions and low carbon footprint.
- The ability to reach previously inaccessible areas.

Research partners the Universities of East Anglia and Exeter highlighted a need to collect data in the Southern Ocean. This presented inherent challenges, particularly in winter. An autonomous vessel could provide the solution, but it would need to be able to navigate to avoid small ice, sustain very cold temperatures, be able to self-right itself when capsized, and would need to self-generate electricity during long periods of darkness.

C.6.2 — Project overview

AutoNaut, a company that designs, builds and operates entirely wave propelled uncrewed surface vessels (USV), formed a consortium and secured Innovate UK funding to develop and test an autonomous vessel that can withstand the extreme environment of the Southern Ocean. AutoNaut worked with University of East Anglia (UEA) which has a seawater ice chamber essential for testing; and University of Exeter's energy harvesting department. The Scottish Association for Marine Science (SAMS) partnered in the 'Extension' bringing in other research institutions such the National Oceanography Centre (NOC), Irish Marine Institute, the Galway Mayo Institute of Technology, CEFAS, and the UK Met Office. Also international projects such as iFADO became partners during the 'extension' ocean testing stage.

The project involved researching and testing multiple aspects of the vessel including its ability to harvest energy, navigate past small ice, ice abrasion, and anti-icing solutions. Many of these tests took place in UEA's seawater ice chamber. The vessel was then tested in the Atlantic Ocean covering some 4,000 nautical miles zig zagging down the continental shelf break gathering data between Oban and Penzance. The project was also supported by sensor manufacturers loaning equipment and analysing data: these were Nortek Signature500 Acoustic Doppler Current Profiler (ADCP); Xylem Aanderaa Motus wave sensor; Seiche micro passive acoustic monitor (uPAM). UEA loaned their Seabird conductivity, temperature and depth (CTD).

C.6.3 — Key outputs, outcomes and impacts

This mission in the Atlantic successfully validated the research and development and the project was deemed to be a success. The tests were successful on all measures except for energy harvesting: testing for this has been ongoing at University of Exeter and by AutoNaut, and a separate solution is being sought.

The vessel has proved to be commercially viable with multiple applications. An AutoNaut vessel has been sold to a European Institute which is due to be deployed in the Arctic, another in the Southern Ocean, and four vessels have been sold to the Caribbean to take part in hurricane forecasting.

This programme assisted AutoNaut's involvement in wider initiatives. This includes: collaboration with **Plymouth Marine Laboratory** which sourced an AutoNaut for scientific missions off the coast of the UK; Marine Management Organisation's **Blue Belt Programme**; and the **Fast Cluster**, a group or organisations around Plymouth focused on autonomy, technology and the ocean. These initiatives and the testing at sea generated media coverage including from the local BBC station, ITN and an invitation to take part in a podcast. University of East Anglia published an **article** on the first use of their 5m AutoNaut off Barbados. This USW 'Caravela', which deploys an underwater autonomous vessel (robot launches robot) is programmed to operate in the Southern Ocean in 2023–2024.

Academic outputs include a **paper** written by the team at the University of Exeter. The partners gave talks at a number of conferences in the UK and Europe. AutoNaut connected an international paint manufacturer with UEA so they were able to utilise the lessons learnt about the vessel coatings in extreme cold and ice, and they have commissioned further tests which has resulted in further income and research for the University. Data gathered during the trial in the Atlantic has been distributed freely.

The project has supported net-zero ambitions by using zero carbon propulsion to capture data to better understand climate patterns and climate change. The technology also has scope for being utilised more widely, for example in monitoring for offshore wind developments and oil rigs, illegal fisheries, and for military applications.

C.7 — SMARTER

C.7.1 — Project rationale

The SMARTER (Space Manufacturing Assembly and Repair Technology Exploration and Realisation) project was intended to develop technologies for the manufacture, assembly and repair of assets, such as satellites or other spacecraft, or for the manufacture of components for large-format structures (such as antennae) in space. It currently costs a great deal to build something on earth and then launch it into space. Manufacturing in space seeks to reduce this cost and widen the possibilities of what can be built.

Manufacturing in space is subject to extreme conditions, such as extreme temperatures, high radiation and low or zero gravity. As such the project was intended to address and negotiate these fundamental challenges and explore how space manufacturing could develop in the future. The project's aims were to assess existing technology and processes against the requirements of the extreme space environment, to understand which technologies can be used in space now, where the challenges and gaps are, and where and how technologies will need to be matured to overcome these challenges.

C.7.2 — Project overview

The lead organisation for the project was BAE Systems, a British multinational defence, security, and aerospace company. BAE worked with the University of Nottingham, the Manufacturing Technology Centre, the Satellite Applications Catapult and four SMEs (Printed Electronics Ltd, Magna Parva, Lena Space and Reaction Engines).

The project chose to focus on automated additive manufacturing and automated assembly, disassembly and repair technologies. As well as work packages exploring existing relevant processes and technologies and identifying potential technologies for the project to pursue, the project team developed and demonstrated an intelligent, self-checking robotic system for assembling panels into an antenna. The demonstration was intended to take place face-to-face but ultimately took place virtually due to lockdown restrictions.

C.7.3 — Key outputs, outcomes and impacts

The project successfully demonstrated technology with intelligent and autonomous assembly capability using a combination of off-the-shelf parts and bespoke hardware. It also identified the fundamental challenges, gaps and areas for future exploration in terms of what would be required for this technology to work in the space environment: for example, storage capacity, heat dissipation, and communications. The consortium bid for funding to continue developing the project to meet the constraints of the space environment and testing it in simulated space conditions. However, this bid was not successful.

Several key partners believed the project had increased their credibility in the space sector. BAE Systems felt that the funding had facilitated and enabled their re-entry into the space sector and that this was now a core part of their business, with their presence within this sector growing. Participating in the project prompted MTC to undertake an exercise identifying what they could offer the space sector though applying their expertise. This resulted in a project to determine how MTC could support the burgeoning UK space sector, including a brochure which they presented at the Made for Space conference in 2019 and the recruitment of a business development manager for the space sector. There is currently no existing market in in-space manufacturing, but BAE aims to develop this into a niche market that the UK is well-placed to exploit due to its strong space and aerospace sectors.

Manufacturing in space needs to be highly efficient due to resource constraints, including making use of high-efficiency AI: research in this area can therefore contribute to, and be informed by, the goal of making manufacturing technology and AI more efficient in general to increase sustainability and support net zero ambitions. BAE reported that they are currently undertaking several research projects related to efficient manufacturing. These have been informed by the experience with SMARTER in terms of developing intelligent systems for environments with constrained resources, and considering how processes generating large amounts of data can be managed to provide operators with useful information without overwhelming them.

C.8 — Prometheus

C.6.1 — Project rationale

The purpose of this project was to facilitate the inspection of voids, such as subterranean mines, which lie below the rail network. There are around 5,000 known mines under the network, many of which have not been investigated since they cannot be accessed. These present a hazard to rail infrastructure, putting trains at risk of derailing should they collapse. Since the mine environment is beyond-visual-line-of-sight (BVLOS) and a GPS denied environment, piloted operations are not feasible. It currently costs £200k per mine to carry out inspections, with 40 mines inspected per year.

A robotic solution could provide a cost-effective alternative to human intervention and allow more voids to be inspected. The aim for the Prometheus project was to develop a drone incorporating robotic and AI technology which could be deployed and retrieved through a restricted entry port, autonomously navigate through the mine, and undertake geo-technical surveys of the mines in non-GPS areas BVLOS. The ultimate goal was to produce a commercially viable product.

C.8.2 — Project overview

The project was led by Headlight AI, an AI software developer, working with Network Rail; Thales who led on the design of the situational awareness activity; and Callen-Lenz experts in commercial drone operations. There were three academic partners: University of Manchester led the activity in system integration and demonstration, Bristol University were responsible for designing the drone required to enter the mine tunnel as well as the advanced control, power management and drone retrieval mechanism, while Royal Holloway University of London led the activity on drone planning, navigation and exploration, including multiple drone operations. By the end of the project, the partners aimed to have produced a design specification and a prototype version of the technology, and a methodology for safe deployment and operation of the technology through boreholes. They also wanted to have demonstrated the prototype in a safe mine; and have developed a plan for future development and exploitation of the technology.

C.8.3 — Key outputs, outcomes and impacts

The project team successfully developed a suite of technologies to locate, map, inspect and organise subsurface assets. "Dragonfly", a 360-degree sensing system using multiple lightweight sensors, was designed and built for use on-board the drone. This system produces a 3D point cloud which allows it to "see" in the dark. With its advanced software integrated, this device was able to capture 3D data, sense obstacles, map and plan flight paths even in pitch dark environments.

The project was a success in that it resulted in the design and development of a drone that met its objectives in subterranean spaces. The tests were more successful than was hoped. The drone was successfully deployed through a 150mm borehole, and the project found that the drone's performance was barely limited by being in a confined space away from the line of vision. It was successfully proven that an autonomous robot could work where there is no GPS signal BVLOS, navigate unknown regions autonomously and return within 20 minutes.Headlight AI are continuing with further trials of the technology in 2023.

However, the hope that this would materialise into a commercial proposition was not realised as Network Rail decided not to invest further. The project team explored other potential applications in the security sector, for instance to secure underground tunnels. However, no commercial partner has yet been found.

Headlight AI felt that the funding has allowed them to better connect with the RAI science base and that the learning from this project could help develop more RAI solutions. A joint scientific paper was published by Headlight AI and the academic partners. The drone was put on display in the National Railway Museum in York on 11 January 2023 as part of its Autonomous Technology season.

C.9 — RADBLAD

C.9.1 — Project rationale

The UK has a target for all electricity to come from 100% zero-carbon generation by 2035. As a result of these policy requirements there has been a significant growth in the installed wind power capacity within the UK. This rapid growth presents a growing challenge in terms of the maintenance of wind turbines: preventative inspection is required every 3–4 months and maintenance every 6 months. Furthermore, because of the extreme environments that these inspections and maintenance take place in, accidents are not uncommon.

In response to this challenge, the RADBLAD project was intended to provide a safer, more efficient and higher quality inspection method, removing the need for on-site human inspection. It was envisaged as a first of-of-its-kind magnetically adhering wall climbing robot with a manipulator arm that deploys an x-ray system around a turbine blade. Algorithms developed by the project then analyse the x-ray images.

C.9.2 — Project overview

The project was led by Innvotek and consisted of two phases. The feasibility study in Phase 1 demonstrated the applicability of the technology and took the project to a technical readiness level (TRL) of 4. The project was able to acquire x-ray images of sample wind turbine blades to develop the algorithm to detect and classify defects, and build the x-ray equipment with the requisite specifications. While the climbing robot was not tested in actual conditions, the project developed a robot that was able to climb similar surfaces using magnetic force and a mechanical motor system. However, Phase 1 did not include lab testing and so the technology was not mature enough to attract private investment. Therefore, the broad objective of Phase 2 was to achieve TRL 7 by testing a fully developed prototype in operational conditions, using OREC's offshore demonstration turbine in Levenmouth, Fife. This phase included scaling up the prototype from phase 1, integrating the different components of the solution, in-field testing, and testing of the defect recognition algorithm using real-world data.

C.9.3 — Key outputs, outcomes and impacts

As the project developed and the design and scale of the robotic system changed, it became clear that it would not be possible to test the technology on a full-scale turbine. The project was therefore rescoped to involve a prototype assembly at Forth Engineering and smaller-scale testing at the OREC facilities in Blyth. However, once the prototype had been built and some smaller-scale testing was done, it was also deemed too risky to test the prototype as planned since the structural integrity of the robot was not as intended.

Although the RADBLAD project has not been taken forward, it heavily informed the development of a new product for Innvotek, Amphibian. This is a robotic platform designed for remote use in harsh marine environments: it can crawl on surfaces and inspect structures up to 60m underwater. Amphibian has been informed by RADBLAD in three ways: its modular design which can be adapted to perform different tasks; the use of magnetic wheels in wet and windy conditions; and agility to go around surfaces which are curved or vary in shape. Innvotek have further secured a contract with General Electric to adapt the Amphibian technology for bolt tightening inspection of GE's offshore wind turbines; and signed several global distribution agreements to distribute the Amphibian platform for use Oil & Gas, Ship-Care and Offshore Wind.

OREC is expanding its Blyth facilities for robotics and autonomous systems, including a new £3m offshore wind robotics centre. The development of these facilities has been informed by OREC's experience with RADBLAD: for example, considering what appropriate success criteria are for robotic testing and how to measure these; and how the facilities can be used to set up simulated operations with which to test the technology.

C.10 — Piglet/InSight

C.10.1 — Project rationale

The safe and efficient transmission of natural gas is dependent on pipelines and vessels being free from contamination. To achieve this, gas processors sometimes "pig" (scrape) pipelines up to 4 times a year. However, this results in lost productivity and can be unsuitable if pipes go around corners or have internal structures which prevent the pig moving through the pipe. Treatment vessels can require human inspection, with risks of exposure to harmful chemicals and fire.

The project aimed to design a robot that could operate in this environment, providing anefficient way to remove contamination and thereby reducing or preventing the need for shutdown. A snake robot was needed to enable navigation of the often-tight spaces and narrow entry points, as well as being sufficiently robust to withstand the environment. While snake robots are already used in other contexts, this use case required that the robot, particularly the head, could be remotely controlled.

C.10.2 — Project overview

The project was led by Process Vision Ltd, working in a new partnership with the University of Reading and drawing on their capabilities in designing robotic control systems, mathematical modelling and electronics to develop the control systems for the robot. It aimed to build on Process Vision's existing product, LineVu, which detects contamination in pipelines. The planned project output was a functional prototype that could be used in demonstrations to seek feedback from potential customers and inform future development.

Two phases of the project were funded by Innovate UK and included both hardware and software development. Phase One supported the development of an initial prototype, featured in a demonstration video. Phase Two enhanced the design, including increasing the number of joints in the robot and changing from electric motors to hydraulics to allow for greater manoeuvrability and remote operation. A final phase covered commercial preparation including IP strategy and formulation extension.

C.10.3 — Key outputs, outcomes and impacts

While snake robots themselves are not new, the key developments within this project have been to demonstrate the potential to inject them into a high-pressure environment, and to include a control system to allow remote operation of the robot head.

The first phase included a presentation at the International Petroleum Technology Conference (IPTC) in January 2020 in Saudi Arabia and the Gas Processing Association Conference, also in 2020, online. The research was also written up in the University of Reading paper "Developing a Leader-Follower Kinematic-Based Control System for a Cable-Driven Hyper-Redundant Serial Manipulator". The collaboration between the company and University of Reading also led to Process Vision sponsoring a PhD, whilst increasing the researchers' interest in future industrial collaborations, and the visibility of, and trust in the robotics school within the University.

The project and exposure at the above conferences have led to conversations that have suggested a wider range of uses than originally envisaged. Process Vision has been in discussions at Director level with global utility companies including three to four major oil and gas operators. A key target market is now expected to be in inspecting and cleaning heat exchangers. Other potential applications within utilities include vessel inspection and cleaning, and potential further markets include water utilities and pharmaceutical manufacturing, as well as uses in mine clearing or search and rescue.

Discussions with potential customers are ongoing. Customers have suggested further areas for development such as incorporating a magazine of tools to allow for different features within the pipelines to be inspected. There are now plans for a self-funded Phase 3, based on feedback from potential customers, which aims to reduce the space taken up by the robot outside the pipeline and increase the distance along the pipeline that the robot can be inserted.

C.11 — In-Orbit Servicing Control Centre (IOSCC) National Facility

C.11.1 — Project rationale

There are currently upward of 8,000 satellites orbiting the Earth, of which around 4,800 are active[1]. Between 2021 and 2022, the number of satellites increased by 11.84%, and will continue to increase over the next 10 years by an estimated 17,000.[2] This increase is driven on the supply side by the development of compact satellites which can be launched simultaneously in larger numbers, thus decreasing launch prices per satellite. As the number of active and obsolete satellites increases, the risk of in orbit collision, Kessler Syndrome and the resulting debris belt increases exponentially. This poses a significant hazard to the future of the space industry and all its benefits.[3] Given the strategic importance of the zone occupied by satellites, not only for long or short-term orbit but as a thoroughfare for future space exploration, the growing number of objects in orbit around Earth is not sustainable and requires intervention.

C.11.2 — Project overview

In response to this challenge, the purpose of the National IOSCC project is to facilitate and demonstrate a world-first capability; the safe and targeted deorbiting of a target satellite. Once the capability has been proven, the facility will be made available for commercial use. It is hoped that it will become a hub for similar activities going forward, given the market potential in the in-orbit servicing and manufacturing sector (IOSM).

The project, led by Astroscale, which is the first private company with a vision to secure the safe and sustainable development of space, and in partnership with the Satellite Applications Catapult, will consist of two essential elements. The first being a ground-based facility with the necessary functionality to monitor and communicate with assets in space that are embarking on close-proximity missions. The second component is to demonstrate the capture of a satellite and facilitate its removal from orbit, using the IOSCC as the base of operations for the mission.

C.11.3 — Key outputs, outcomes and impacts

The first element of the IOSCC project, namely the delivery of the ground control facility itself, was completed in time to launch Astroscale's ELSA-d, the world's first commercial mission to prove the core technologies necessary for space debris docking and removal.. Through Astroscale's ELSA-d mission, IOSCC ground control and in-orbit aspects successfully benchmarked several of these functions and paved the way for future missions.

The IOSCC project has led to follow on activities for the Satellite Applications Catapult and for Astroscale. The Catapult is currently in talks to host a handful of active debris removal (ADR) projects through the UKSA Fund, many of which are being led by private operators like ClearSpace and Space Forge. The Catapult's involvement in the In-Orbit Servicing and Manufacturing Group and the Space Energy Initiative is complementary to their participation in the IOSCC project. These groups eventually led to the creation of Space Solar Ltd, which aims to deliver space-based solar power commercially within the next decade.

For Astroscale, the successes and lessons learned from ELSA-d have led directly to a follow-on mission with commercial promise; ELSA-M (Multiple client). Designed for 9 years of service without refuelling (the useful lifespan would increase with the possibility of future refuelling and recycling missions), ELSA-M is Astroscale's flagship End-of-Life service. OneWeb is the prime for an ELSA-M In-Orbit Demonstration (IOD) mission with partial funding from UKSA and ESA. Expected to launch in 2025, the ELSA-M servicer is on track to be the world's first commercial venture designed to capture and remove failed satellites and dispose of them safely.

C.12 — Robots Under Ice

C.12.1 — Project rationale

Due to climate change, the ice cover in polar sea regions is reducing. This opens up new areas for energy exploration giving access to new oil and gas fields. It also provides opportunities to open new shipping lanes, such as the 'Northwest Passage' to the Pacific Ocean through the Arctic Sea north of North America.[25]

The risks of operating in these extreme environments, where seas are still seasonally ice bound, are still very high, and a better understanding of the risks of operating near the ice is required. Autonomous Underwater Vehicles – a technology used by the industry in other environments – can help accomplish this, e.g., by surveying the underside of icebergs and estimating the probability of break-up. Such mapping has been undertaken for academic studies, but further technological developments are required to make the technology viable for commercial use in the arctic, e.g., reducing the risk of losing vehicles and failing to collect data.

The Robots under Ice project set out to conduct a study of the technology and operational developments required to make under-ice AUV operations to collect ice hazard data viable. Successful deployment of AUVs could ultimately help increase safety in operations by reducing human intervention, as well as reduce time and cost of such surveys.

C.12.2 — Project overview

The project, 'Robots Under Ice: Gathering Ice Hazard Data from Below' was funded by Innovate UK as a collaborative R&D project, with a budget of £146,566. The project was meant to run from January 2018 to June 2019. The study investigates the feasibility of deploying under-ice AUVs for determining ice hazard risk to energy infrastructure and shipping in the Arctic Sea and ultimately put technologies in place which can enable effective commercial use of AUVs for these purposes. The project is a collaboration between Cambridge Polar Consulting and the THURN Group, who combine scientific expertise with advanced undersea applications experience.

The project included 6 work packages within two distinct phases, with phase 1 focusing on feasibility and phase 2 intended to be focused on applications of the technology. Ultimately, the project did not implementation of technological solutions, despite exploring a variety of options. The team was able to collect valuable data and engaged with a variety of companies and governmental bodies during phase 1.

C.12.3 — Key outputs, outcomes and impacts

The project was ultimately never completed, with limited technological opportunities arising from the phase 1 activities. The project team originally projected that they would develop an initial batch of 5 missions per year, generating £1.9m in turnover, but this will not be realised.

The project was dependent on acquiring external funds to support these further developments in phase 2. Despite the inability to meet expectations, the project team was able to gather useful data and contacts during the project which they hope to leverage in future research and applications.

Project participants acknowledge that the project failed to deliver on all objectives within the timeline of the project, but they nevertheless found it worthwhile. In their view, the project completed the 'feasibility' part of the study, arriving at the conclusion that there wasn't sufficient interest within the industry to justify further investment at this point. While disappointing, this was seen as a natural outcome for such inherently uncertain projects.

Despite the inability of the project to gather additional funds, there were lessons learned for the project team and Innovate UK about what allows a project to succeed. There was a recognition that further support for from Innovate UK may have helped the project team better understand and meet Innovate demands and reporting requirements. This is critical if Innovate is attempting to attract new actors without years of bidding and delivery experience. The lack of clear customers for early applications of the technology was novel but ultimately failed to generate enough sales to continue. Including launch customers in bids is viewed as a potential means to overcome this obstacle but could also increase administrative costs.

C.13 — ROVCO (AUV3D and A2I2)

C.13.1 — Project rationale

The strategic importance of the offshore energy sector has increased[1] in the wake of the current energy crisis[2], and as calls for Net Zero grow. Growth in the number of offshore assets is expected to result in higher demand for the inspection and maintenance of these assets. However, conditions offshore are hazardous; extreme weather and remote locations result in dangerous missions that require specialised staff and equipment. These in turn drive up the cost of inspection, which may not be feasible given the projected growth of offshore assets.

As part of the ISCF RAI challenge, ROVCO has developed a camera system capable of mapping out a 3D model of the asset by performing consecutive sweeps across the surface. The compilation of a 3D model means that accurate data is always on hand without the need to search through video archives. The system's simultaneous localisation and mapping (SLAM) capability is also a necessary precursor for a fully autonomous underwater vehicle (AUV) which requires no communications tether and is able to navigate tight spaces without the risk of collision or damage to the asset. The development of such an AUV forms the other part of ROVCO's participation in the ISCF RAI challenge. Ultimately, the technology has the potential to improve offshore asset management by increasing accuracy and enabling significant savings from automated navigation and image processing while limiting the need to need to bring analysts offshore for inspections.

C.13.2 — Project overview

A series of five grants has been awarded to ROVCO since early 2017. The projects focused on ROVCO core technology offerings, starting with feasibility and progressing to proof of concept and demonstration, and including the integration of technologies onto more complex platforms. Although the projects don't necessarily build directly on each other, they all aim to contribute to the development of ROVCO's camera system and its deployment on underwater vehicles. The objectives of each project are summarised overleaf.

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[25] See e.g. OCIMF, "Northern Sea Route Navigation: Best Practices and Challenges", First edition (2017)

- Real Time 3D modelling for Subsea Asset Management: A small desk-based feasibility and business case study about the potential to use vision systems to collect 3D data underwater. The study served to determine the viability and industry readiness for this solution.[5]
- **AUV3D phase 1** – the scope of the first project covered technical feasibility, aiming to prototype and demonstrate a high-quality underwater, intelligent, stereo camera system.[6] The system would be able to locate itself and the subject of its inspection based on incoming and processed visual data, allowing it gradually build complex 3D models.
- **AUV3D phase 2** – picking up directly from phase 1, this project aimed to improve the robustness of the software and demonstrate it in subsea conditions. The project aimed to develop a more complete solution, including integration with additional sensors and the delivery of live survey data to shore.[7]
- **A2I2** – The result of an innovation lab event held in 2018, the project aimed to build two tetherless AUV inspection prototypes:
  - One for offshore use (led by ROVCO and NOC).
  - One for use in nuclear storage tanks (led by Forth Engineering and the University of Manchester).

The project, led by ROVCO, was also supported by partnerships with the Offshore Renewable Energy Catapult, the National Oceanographic Centre, D-RisQ, and Nuclear Storage Pool Prototype Partners. Each partner contributed their expertise to the project, with all partners receiving funds except Nuclear Storage Pool Prototype Partners.

C.13.3 — Key outputs, outcomes and impacts

ROVCO, the project lead, has experienced several benefits as result of ISCF RAI participation and funding. Most saliently, consecutive projects in which their focus has remained their intelligent camera system have allowed ROVCO to progress from a feasibility study to the commercialisation of a mature technology. The ISCF grants have directly funded the growth of the company's R&D team, and the projects have enabled access to skills, knowledge and facilities through partnerships and collaboration. Participation has enabled the company to improve the quality of their services to clients, which has indirectly led to the expansion of their business model from a technology developer into a robotics services provider. In the first few years of ISCF funding, ROVCO grew rapidly; in 2018/19, turnover increased to £10m, up from less than £0.5m in the previous year.[15] This growth has allowed the company to increase its staff from 3 employees in 2017 to more than 80 by the end of 2022, including the Vaarst subsidiary.[16]

The ORE catapult, a partner in the earlier AUV3D projects, was able to improve their testing facilities for robotic subsea systems as a result of their participation and ISCF funding. The ORCA hub subsequently benefited from ORE's new facilities.

The NOC benefited from the addition of a new AUV to their fleet; where their existing AUVs have been torpedo shaped and less manoeuvrable, they have gained a hover-capable vessel through A2I2. This new class of AUV benefits the scientific work the NOC conducts, and also lays the foundation for a product that the NOC will eventually commercialise once the technology has reached the required maturity. The follow-on projects (SEAMless and beyond) will contribute to progress in the vessel's maturity. As an organisation, the NOC have also been able to expand their skillset as it relates to vessel control by the addition of this new class of AUV.

The verification software partner on A2I2, D-RisQ, primarily benefited from the strengthening of their software engineering capabilities and the tools that had been developed for the project. This has aided them in their bids for new projects. D-RisQ's work has also been recognised beyond the scope of the programme, and members of staff currently hold leadership positions on the OLTER programme for autonomous offshore energy inspection and maintenance.

C.14 — WormBot

C.14.1 — Project rationale

The WormBot project is intended to support the development of robots for use in hard to reach places, capable of operating without input from an operator. There are many types of robots currently being used for nuclear site surveys, disaster zone assistance and even infrastructure inspections but are often too cumbersome and complex for many of these environments. The WormBot project will take steps to alleviate those concerns by developing lightweight, components for a new robot that can be deployed in their own business but also benefit the wider UK economy in the long-term.

The current generation of robots in use for nuclear decommissioning and disaster zone relief are often adapted from other industries, limiting their effectiveness in complex working environments. The application of these technologies, allowing for more manoeuvrable and capable machines in smaller spaces, will improve the speed and precision of future operations. The ability to operate in small spaces will guide the work of personnel on site, either focusing their attention or redirecting their attention to areas in greater need of their presence.

C.14.2 — Project overview

Q-bot is a company that specialises in using robots to insulate commercial and residential dwellings, particularly underfloor insulation in hard to access areas. Q-bot, the lead of the WormBot project, has received a number of Innovate UK grants in recent years. Of particular interest is the InspectorBot project that ran from October 2017 until March 2019. This prior project focused on developing technology that could be deployed in infrastructure inspection, particularly in underground or confined spaces. They have a history of receiving grants from Innovate UK since 2012.

Alongside Q-bot, the project involves a partner and a subcontractor to support the R&D process. The partner on the project is the Centre for Advanced Robotics, QMCL, who bring extensive experience and expertise in developing advanced robotic components. Imperial College London will act as a subcontractor on the project, focusing on developing any operational prototypes into manufacturable designs.

C.14.3 — Key outputs, outcomes and impacts

Q-bot has been able to develop a more advanced robot to use in its existing business. This will improve its ability to access all areas of a customer's house for insulation application. In doing so, they can achieve better results for the customer and improve their ability to deliver their product in more complex cases. The research funded by this project has increased the speed at which Q-bot have been able to iterate the design of their robot, and make significant improvements in a vastly shortened timespan. The company indicated that the funding has likely cut up to 2 years off their previously predicted plan. As detailed below, Q-bot has seen further research funding to expand their business operations into new application areas increasing their potential customer base going forward.

QMUL has found a willing and able partner to test and trial advanced technology. This allows their lab work to find its way into the field with lower costs and effort. The funds from the ISCF have been able to support 3 researchers within the laboratory, improving the speed at which they were able to advance their research. QMUL has maintained its relationship with Q-bot, with 3 PhD students being funded as part of this work. Successful researchers are in high demand, with some moving to Q-bot or other application companies due to their contributions to WORMBOT.

The project team was successful in generating two Innovate UK follow on projects as a result of their success with Q-bot. The two projects ran in parallel running from 2021 into 2022. The two projects, GROWBOT and LIANABOT followed two distinct pathways for development with GROWBOT focusing on a movement system that could maintain a sensor suite at the front of a moveable robot and LIANABOT taking the Q-bot design and adapt it to function in wall cavities. Both have proven their applications are viable (TRL 4–5) and will be further developed into the future.

C.15 — LONG-OPS: A UK-Japan R&D programme to develop long reach manipulators for use in long term remote operations for nuclear decommissioning

C.15.1 — Project rationale

Robotics and AI technologies have been recognised as technologies that could considerably improve the existing technological foundation for decommissioning the UK's nuclear legacy as part of the Nuclear Decommissioning Agency's (NDA) work on emerging technologies. Further advancements in RAI technology could make UK nuclear decommissioning faster, cheaper, safer, and less environmentally damaging.

LONG-OPS is a research and development programme funded by a £12 million UK-Japanese partnership that aims to examine and expand the capabilities of digital robotic technology for application in the decommissioning of nuclear and fusion energy facilities. LONG-OPS refers to the project's emphasis on the use of digital tools by operators to control long-reach robotics in extended operations.

C.15.2 — Project overview

LONG-OPS is a four-year research and development effort that combines three nuclear operations use cases: decommissioning in the United Kingdom, decommissioning of the Fukushima Dai-ichi reactors in Japan, and the design of the first remotely operated fusion reactors. This singular international partnership is financed equally by UKRI, the NDA, and TEPCO (Japan) who invested £4 million each. The supported projects will drive advances in architecture and standards, digital mock-ups, technology development related to long reach robotic systems, haptic manipulators, and sensing systems in complex/ unstructured environments. Decommissioning research will be focused on the UKAEA Joint European Torus fusion experiment, the UK Nuclear Decommissioning Authority Strategy, and the ongoing process of decommission the Fukushima Daichi Nuclear Plant.

A significant component of the LONG-OPS is the development of a sophisticated digital twin technology, a software suite that can mirror the physical world in virtual reality. The next generation digital twins being supported by this project will allow engineers and government agencies to develop decommissioning strategies, while also providing training opportunities for operators in high consequence complex environments.

C.15.3 — Key outputs, outcomes and impacts

ISCF funding for LONG-OPS is only the start of this research, with the initial investment only covering the first two years of a four-year programme. As the end of the Innovate UK funding approaches, the project has, thus far, met all its objectives that were laid out in the project plan. Much of the work to date has been about building capacity in nuclear decommissioning, developing a robust supply chain for the sector, and upskilling individuals through the sharing of knowledge and expertise. To date, few financial benefits have been generated, although they are expected in the future.

Although meeting objectives is key, this investment is seen as only the first step in fostering further collaboration. The success of the project has led to participants already planning a LONG-OPS 2 as well as the Robotics and AI collaboration (RAICo), a collaboration between NDA, Sellafield UKAEA, the University of Manchester, and NNL. The development of these two new initiatives has caused a fundamental shift in UK strategy in relation to nucleardecommissioning investments. The continuing success of this programme is driven by people, with the development of new relationships and maintaining trust and commitment from all parties.

Ultimately, the goal of LONG-OPS is to identify gaps in existing capabilities in nuclear decommissioning operations. By joining with Japan, UK experts have an opportunity to pool knowledge to find solutions to the most stubborn and complex problems that the entire nuclear industry in facing. The success of the project has meant that there will be direct follow-on projects, but also new collaborations and research being conducted that was entirely unexpected and novel. This will drive innovation and growth in the sectors for all partners.

C.16 — Shared Waterspace Autonomous Navigation by Satellites (SWANS)

C.16.1 — Project rationale

Automation technologies, decision support systems, and autonomous navigation systems are becoming more prevalent in shipping. These advancements are motivated by the fundamental need to ensure the safe and efficient operation and navigation of ships. Collision avoidance is the primary responsibility for automated or autonomous navigation systems, in addition to preventing groundings and maintaining steady navigation amid erratic weather in the deep sea.

SWANS is a research and development programme aimed at developing and implementing innovative solutions for improved use of shared waterspace by traditionally manned, partially automated, and fully autonomous surface vessels.[4] By developing the first safe over-the-horizon operating system for congested waterways that is commercially ready, the programme aims to remove existing obstacles.

C.16.2 — Project overview

SWANS is a £1.2 million research initiative financed by Innovate UK, the U.K.'s innovation agency. This project is being led by BMT Ship and Coastal Dynamics Limited, with L3 ASV (formerly ASV Global) and Deimos Space UK as partners. This project is a continuation of over- the-horizon operations from L3 ASV that were completed with their fleet of ASVs using advances autonomous navigation systems.

The primary emphasis of SWANS is the interaction in potentially dangerous scenarios between mariners in conventional manned craft as they perceive and respond to ASVs operating over the horizon (beyond line of sight) and in close proximity to other vessels using newly fused visual and satellite data. Pilots, other mariners, and marine insurers must be led and trained on how to respond to this developing ASV technology as it enters a quickly expanding market.[4]

C.16.3 — Key outputs, outcomes and impacts

SWANS has demonstrated a series of integrated simulators that combine operational awareness, over-the-horizon optimised unmanned navigation, and operating in congested waters with manned vessels.

Demonstrations have been given of the usage of both manned vessels in unmanned mode and an unmanned vessel in autonomous mode operating over the horizon at sea as well as in crowded waters such as ports, navigation channels, and inland waterways. A digital forensics module has been created for the integrated simulators that enables quick visualisation. Lessons have also been gathered through simulations of circumstances where there is a very high danger of contact or collision.

The completion of work packages covering Training and Environment Simulation, as well as the development and testing of a human and unmanned conflict prediction tool, will now feed into recommendations for safe operating regulations and updates to the International Maritime Organisation (IMO) working group on autonomous vessels.

Commercialisation has been swift, with BMT simulators being adopted by numerous human and autonomous ship operators, as well as the world's top statutory marine accident investigative agencies. These include international counterparts in the Netherlands, Australia, and Singapore as well as the US National Transportation Safety Board and the UK Marine Accident Investigation Branch.

C.17 — A UAV based logistics capability for use in military and civilian missions

C.17.1 — Project rationale

The use of UAVs in the delivery of essential supplies like vaccines to remote areas has become increasingly common over the last decade.

Even prior to the onset of COVID-19, governments of nations like Malawi, where many communities are hard to reach by other means, set up drone corridor networks to deliver childhood vaccines for Malaria, TB and rotavirus. These same networks were used to deliver COVID-19 vaccines, and have since expanded to include more common prescription medications. Drones are also being trialled in remote regions of the UK, France and Canada for the delivery of small parcels. This application holds some advantage over land-based methods, especially for reduced carbon emissions and delivery times.

The UAV based logistics capability for use in military and civilian missions (UAVL) project aims to develop a drone that can carry heavy cargo (up to 25kg) over large distances (several hundred kms, staying airborne for 6 hours or more) autonomously. For comparison, current high payload drones carry payloads between 4–8kg for ranges from 10km to 35km or flight times of under an hour.

C.17.2 — Project overview

The UAVL project began as a competition call by the MOD to develop ground-, air- and sea-based logistics solutions. The challenges to be addressed were those of payload capacity, distance and mode of delivery. Barnard Microsystems Limited (BML) submitted a proposal to develop a UAV capable of:

- Vertical take-off and landing (VTOL) as well as conventional take-off and landing (CTOL), to maximise the kinds of terrain in which the UAV could operate.
- Transitioning between rotary-wing (hover and multiple planes of motion) and fixed-wing (forward) modes while in the air which allows for complex manoeuvres as well as high speed over large distances.
- Cargo release via direct delivery after landing or via hot-drop from the air (without the rotors damaging the cargo or its parachute), to accommodate different kinds of landing conditions like tree cover, ship decks or built-up areas.
- Mission autonomy, including on-board decision-making capabilities. These are necessary in case of disruptions to communications with ground control, which are common for long-range and remote missions.
- The combination of the above onto a platform capable of carrying large nominal loads.

The activities undertaken by BML in delivering the UAVL project spanned the development of the UAV platform including the integration of sensory and actuator systems, the on-board software for UAV autonomy as well as the demonstration of the objective capabilities.

As part of this testing and demonstration process, the UAVL participated in a number of events in the US (Coalition Assured Autonomous Resupply 2019) and the UK (attended by the MOD, BEIS and DFID). Upon project closure in October 2019, multiple capabilities had been demonstrated in a piece-wise fashion and in controlled environments; a mission to demonstrate all capabilities at once did not take place.

C.17.3 — Key outputs, outcomes and impacts

UAVL successfully met the objective capabilities with a proof-of-concept drone called the Panchito. Tests were limited to remote areas, however, without flying over people or buildings, so full capability cannot be said to have been demonstrated.

For full demonstration to move forward, BML have continued work on the safety and reliability of the Panchito's autonomy via private venture funding. This additional input is required before transitioning the Panchito from a logistics prototype to a fully industrial model. BML are also incorporating changes within the communications landscape, such as the launch of the Starlink satellite constellation, to improve long-range reliability.

In addition to its success as a logistics prototype, the Panchito UAV is currently fit for market in specific contexts and conditions and sold for autonomous surveillance missions. A portion of UAV sales contributes to ongoing development mentioned above.

As a result of UAVL, BML have benefited in a number of areas:

- BML have designed and constructed a new UAV frame, the Panchito, which has both VTOL and CTOL modes. The drone has a large cargo capacity, in addition to a range of onboard sensory and computational systems.
- They've built new software for use in their autonomous Panchito, as well as improved their software development skills. The software is still in progress for use in logistics contexts, but has already been commercialised for autonomous surveillance.
- Participation in ISCF RAI has enabled them to build networks and leverage these new connections in their marketing activities. For example, BML has taken part in the DTI's international trade missions, which led to international sales of the Panchito UAV.
- The amount of testing required to prove the reliability of autonomous software in the target contexts has built their experience in formal demonstrations. This kind of experience improves understanding of and engagement with regulators and reduces unnecessary and costly delays.

The firm is currently well placed to take advantage of the growing market for UAVs, particularly in remote contexts where land- or sea-based missions are more costly or slow, or have higher carbon footprints.

C.18 — Autonomous Confined Space Inspection using Drones (previously Hybird)

C.18.1 — Project rationale

Large infrastructure projects, such as those undertaken in construction, off- shore & nuclear energy, space and deep mining, often require the inspection of confined, extreme and challenging spaces to analyse and assess the environment for threats and dangers. At present, the inspections are undertaken using personnel or human operated equipment (remote control cars or sewer cameras) with limited freedom of movement and types of data capture. The need to send personnel into potentially hazardous conditions with little or no know information on the level of danger, accounts for around 15 deaths per year in the UK alone, of which 60% occur due to rescue efforts. In addition, the associated costs of mission planning, risk management, maintenance and data capture in confined spaces are high. There, is, therefore, a clear need to reduce both risk of fatality to personnel and address the high costs associated with inspections of confined, extreme and challenging spaces.

At the point of application, only one commercial crash tolerant UAV existed on the market, Flyability's Elios. However, Flyability's Elios only had a maximum of 10-minute flight time and only had the ability to capture visual and thermal data. While, various docking stations existed for large (~7kg) UAVs, at the time of application docking stations for lightweight internal inspections UAVs did not exist. At the time of application, no crash tolerant solutions for extreme internal inspections using UAVs with multiple data capture existed, with a potential market opportunity for this technology being estimated at more than £100bn for nuclear, oil & gas, and infrastructure sectors alone. However, the lack of development with this area was generally a result of technology companies focusing on hardware or software development opposed to integrating the two, which is muchmore complex.

C.18.2 — Project overview

HyBird started the "Autonomous Confined Space Inspection using Drones" CR&D project on March 2018, as part of the first round of CR&D competition of the ISCF Robotics for a Safer World. HyBird aimed to revolutionise confined space entry by developing a high tech miniaturised smart robotic UAV capable of being deployed in an internal or confined space environment and undertake a mission autonomously. This would reduce the risk to personnel, increase productivity and provide substantial time and cost savings – that is provide companies with a safer, faster and cheaper solution to inspecting confined, extreme and challenging spaces.

As mentioned previously, the project integrated both existing and new technology and services from HyBird, project partners and wider suppliers, including:

- UAV docking stations for regular automated flights into confined spaces.
- Lightweight HyBird powertrains.
- Enterprise solution platforms to control UAV operations.
- SLAM for autonomous navigation.
- Flaw detection utilising AI and Machine Vision experts.
- UK based OxisEnergy's lithium sulphur batteries.
- Wireless-charging technology.

HyBird began the project with an early prototype of an inspection UAV, and through the project developed and integrated the autonomous functionality and collision avoidance software, as well as improving other aspects of hardware.

C.18.3 — Key outputs, outcomes and impacts

The project successfully developed a small smart UAV for inspection (Shield XS), a data visualisation and management platform for complex integrity inspection to derive actionable information from the visual inspection data (InSite), and a second platform providing user interface for remote pilot and inspection assistance (OmniSite). HyBird reported that the TRL of the project progressed from TRL 1 to TRL 9 and many of these developments resulted in securing new IP. The Shield XS product is now available on the market, providing end users with a safer, faster and cheaper solution to inspecting confined, extreme and challenging spaces.

Through the ISCF RAI project, HyBird were able to form a new collaboration with end user Costain, a tier one UK infrastructure contractor, and software development company, BeTomorrow. HyBird's collaboration with Constian has continued beyond the end of the project to maximise the commercial opportunities. HyBird also strengthen their existing relationships with project partner AES factory-Avon.

The ISCF RAI funding had a significant impact on HyBird's internal capability, allowing the two founding members to focus fulltime on the business and employ two further software specialists. The project did face challenges in terms of skills availability, however through their ISCF RAI project HyBird have further developed their hiring practices to better meet their future needs.

As a result of their ISCF RAI project HyBird were able to apply and secure a place at the US based TechStars Starburst Space Accelerator. Through this accelerator programme, HyBird were supported to accelerate their business and make significant improvements to their business model and operations with support from mentors and formal sponsor organisations. HyBird have since presented their company to 100+ investors at the TechStars Demo Day, as well as other international conferences for the oil and gas market, further supporting interest in the company which is expected to be exploited over the coming years.

C.19 — Watch Chain

C.19.1 — Project rationale

The aim of the Watch Chain project is to develop remote monitoring equipment which can be used to protect infrastructure from theft, malicious damage or accidents; or to keep areas secure. Oil theft from pipelines is a widespread problem. As well as losses to the economy, theft causes pollution and accidents, and profits from it are often used to fund organised crime. Current technology relies on humans to review evidence and requires a high-bandwidth, reliable data link which it is not always possible to maintain in extreme conditions or at long ranges. Watchchain aims to use machine vision.

The Watch-chain project is supported by two consecutive ISCF-RAI-EE demonstrator grants (phase 1 and 2) and led by Archangel Imaging Ltd. The project aims to use machine vision algorithms which can automatically detect threats. Rather than transmitting all imagery to a server room for analysis, these devices will make decisions on what needs to be transmitted, so that they only need to transmit small amounts of data and only when needed. This means that real-time monitoring can take place and suspicious activity can be detected more quickly.

C.19.2 — Project overview

The aim of the project's first phase was to create an autonomous, smart surveillance device that would use machine vision algorithms developed by Archangel Imaging, and be physically able to be deployed in an extreme environment (small, light and having low power requirements). The device would allow for real-time data processing and analysis, and have reduced need for operation from a control centre. The project would result in a prototype of this device that could be demonstrated to customers and therefore attract interest from customers and private investment.

Archangel Imaging submitted an application in 2018 for the second round of demonstrator funding, under the project name WatchChainR. The application for this phase was made jointly with GMV, a robotics company also based on the Harwell campus, which provided unmanned rover hardware for undertaking the exterior inspections. The scope of the project broadened in phase 2 to include monitoring for the purposes of maintenance as well as security.

C.19.3 — Key outputs, outcomes and impacts

The project lead, Archangel Imaging attributed a number of benefits to the projects. They expected to introduce a product within one year and processes and services within three years, generating an anticipated £5,000,000 in sales revenue and £250,000 in cost reduction per year. They further reported that Two jobs had been safeguarded and anticipated 15 additional roles.

The projects had also influenced their business strategy, bringing them closer to end users and adopting a "collaborative by default" approach with a focus on integrating capabilities with others to create deployable systems.

Within the energy sector, Watchcahin has the potential to reduce oil theft and leakage, leading to economic benefits as well as reduced pollution, accidents and crime. Beyond the oil and gas sector, opportunities are being explored for exploiting the technology in the defence and mining sectors. If used for border monitoring, money will be saved on human border protection, which may result in benefits for the taxpayer. The technology may also have applications for disaster relief, as devices could be deployed to find people in trouble or new dangers, without the need for human surveillance that could expose people to hazards.

C.20 — TeamTao XPRIZE

C.20.1 — Project rationale

In many ways the human race knows more about the surface of Mars than it does about the depths of our oceans. Current estimates place the amount of explored ocean seabed to be at 5% of the world's total, leaving 95% completely unexplored. As climate change continues to impact the planet, there is an increasing need to understand the world's oceans and to incorporate them into our models of the global climate. This lack of exploration also hampers the capability of humans to benefit from the ocean's resources, and to manage and mitigate any negative impacts from such efforts.

As part of these efforts, the XPRIZE Foundation launched the Shell Ocean Discovery XPRIZE with $7m in prize money to help close this gap. The goal of the prize is to accelerate innovation in unman ned exploration capabilities in the deep sea; drive advances in deep ocean exploration and discovery, sustainable resource development, and protection; learn more about the deepest parts of the ocean's depths; and excite the public imagination.[26]

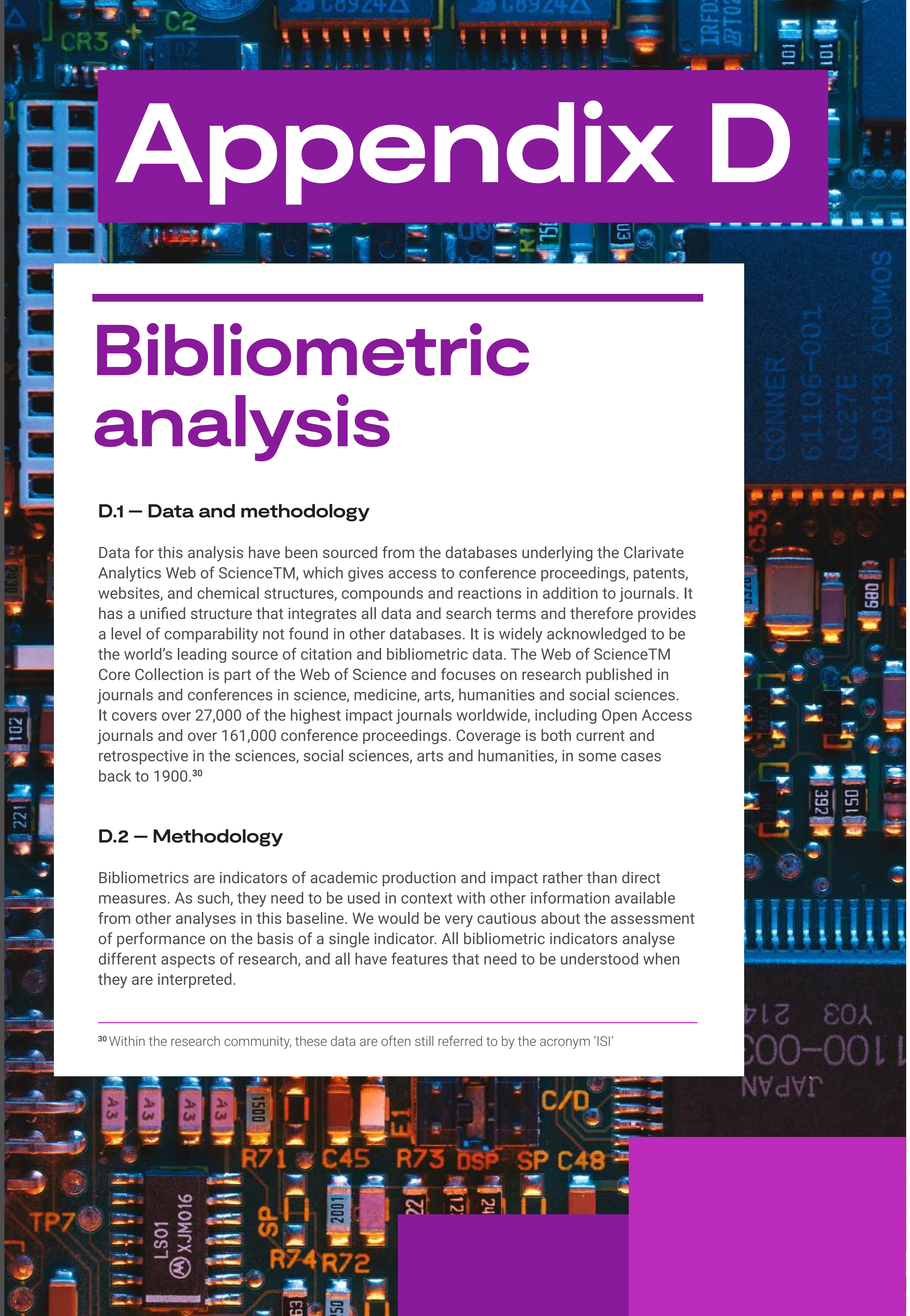
C.20.2 — Project overview

The project requires that the teams compete to develop underwater robots that are capable of mapping a 500 square km area of the ocean floor at a depth of 4km in a 24 hour period without any human intervention. TeamTao, a collaboration between researchers at the University of Newcastle, Soil Machine Dynamics Ltd (SMD). The team came up with a solution to use a low-cost platform, similar to that used in cubesat constellations in space, whereby many devices would work in unison to offer complete coverage of the area. These subsea devices would be launched from an autonomous mothership on the surface that would also provide transit to the search location, data transmission, communications, and charging of the undersea autonomous vehicles. The team ultimately decided on 20 such undersea units, but could scale to increase coverage if needed.

C.20.3 — Key outputs, outcomes and impacts

TEAMTAO was the only team from the UK, and one of the smallest teams globally to reach the grand final of the XPRIZE competition. During the demonstration of their submission, the TEAMTAO underwater autonomous vehicles successfully demonstrated their ability to work in unison to map an area roughly the size of Paris in a 24 hour period. Although the team did not ultimately with the overall prize, the XPRIZE organisation decided to award an additional $200k Moonshot Award in recognition of the team's innovative approach to the competition requirements. The success of the project has been a boon for participating entities and individuals. The ability to achieve such high levels of success, with limited budgets, will lead to further collaborations in the future. In addition, the development of new skills and capabilities within the team will be used on further research and commercial products in the coming years.

[26] XPrize, Discovering the mysteries of the deep sea



Appendix D

Bibliometric analysis

D.1 — Data and methodology

Data for this analysis have been sourced from the databases underlying the Clarivate Analytics Web of ScienceTM, which gives access to conference proceedings, patents, websites, and chemical structures, compounds and reactions in addition to journals. It has a unified structure that integrates all data and search terms and therefore provides a level of comparability not found in other databases. It is widely acknowledged to be the world's leading source of citation and bibliometric data. The Web of ScienceTM Core Collection is part of the Web of Science and focuses on research published in journals and conferences in science, medicine, arts, humanities and social sciences. It covers over 27,000 of the highest impact journals worldwide, including Open Access journals and over 161,000 conference proceedings. Coverage is both current and retrospective in the sciences, social sciences, arts and humanities, in some cases back to 1900.[30]

D.2 — Methodology

Bibliometrics are indicators of academic production and impact rather than direct measures. As such, they need to be used in context with other information available from other analyses in this baseline. We would be very cautious about the assessment of performance on the basis of a single indicator. All bibliometric indicators analyse different aspects of research, and all have features that need to be understood when they are interpreted.

[30] Within the research community, these data are often still referred to by the acronym 'ISI'

All bibliometric indicators have limitations. For example, when analysing the category-normalised citation impact the skewed citation distribution means that one or a few very highly cited papers can influence the average value. A country which produced three papers in a field, all of which were highly cited, would appear to perform very well on the basis of the percentage of highly-cited papers, but this could lead one to draw invalid conclusions if other indicators were not also analysed. To mitigate this, we have excluded from the results countries with fewer than 5 papers per year on average, as this was deemed to indicate a lack of significant research activity in the field of interest. We have also found that the skew can have a very pronounced effect for groups of fewer than 50 papers.

D.3 — Indicators

The study team does not recommend using any one single indicator to infer which country performs best. We would recommend using multiple indicators and from these to triangulate the relative performance. The citation indicators we present in this analysis all focus on different aspects of research impact, and we would recommend that these are considered together in order to draw conclusions on relative performance:

- Average category-normalised citation impact indicates overall average impact but not does not reflect the distribution of citations within a body of research publications.
- Number of highly-cited papers indicates production of papers which have had a high impact on the field(s) to which they relate.
- Percentage of highly-cited papers.

We describe all the indicators used in the rest of the analysis below:

- **Papers/publications** – The terms 'paper' and 'publication' are often used interchangeably to refer to printed and electronic outputs of many types. In this document the term 'paper' has been used exclusively to refer to substantive journal articles, reviews and some proceedings papers and excludes editorials, meeting abstracts or other types of publication. Papers are the subset of publications for which citation data are most informative and which are used in calculations of citation impact.
- **Citations** – The citation count is the number of times that a citation has been recorded for a given publication since it was published. Not all citations are necessarily recorded since not all publications are indexed. The material indexed by Clarivate, however, is estimated to attract about 95% of global citations.
- **Citation impact** – 'Citations per paper' is an index of academic or research impact (as compared with economic or social impact). It is calculated by dividing the sum of citations by the total number of papers in any given dataset (so, for a single paper, raw impact is the same as its citation count). Impact can be calculated for papers within a specific research field such as Clinical Neurology, or for a specific institution or group of institutions, or a specific country. Citation count declines in the most recent years of any time-period as papers have had less time to accumulate citations (papers published in 2007 will typically have more citations than papers published in 2010).
- **Category-normalised citation impact** – Citation rates vary between research fields and with time; consequently, analyses must take both field and year into account. In addition, the type of publication will influence the citation count. For this reason, only citation counts of papers (as defined above) are used in calculations of citation impact. The standard normalisation factor is the world average citations per paper for the year and journal category in which the paper was published. This normalisation is also referred to as 'rebasing' the citation count. An CNCI value of 1 represents performance at par with world average, values above 1 are considered above average and values below 1 are considered below average.
- **Web of Science journal categories or InCitesTM Essential Science Indicators fields** – Standard bibliometric methodology uses journal category or Essential Science Indicators fields as a proxy for research fields. Essential Science Indicators fields aggregate data at a higher level than the journal categories – there are only 22 Essential Science Indicators research fields compared with 254 journal categories. Journals are assigned to one or more categories, and every article within that journal is subsequently assigned to that category. Papers from prestigious, 'multidisciplinary' and general medical journals such as Nature, Science, The Lancet, The BMJ, The New England Journal of Medicine and the Proceedings of the National Academy of Sciences (PNAS) are assigned to specific categories based on the journal categories of the references cited in the article.

- **Number and percentage of highly-cited papers** – Highly-cited papers have had a greater impact on the field to which they relate. We will use papers in the world's top 10% of most highly cited papers (taking publication year and field into account) to indicate levels of scientific excellence.
- **International collaboration** – The metadata associated with every research publication include the addresses of the authors. It is thus possible to develop an analysis of the organisations that co-author publications by extracting and examining these data. Co-authorship is generally accepted as an indicator of collaboration, although there are collaborations that do not result in co-authored publications and co-authored publications which involve limited collaboration. Conceivably, other indicators of collaboration such as co-funding and international exchanges could be used, but comprehensive and consistent data are not available. Papers with authors from more than one country can be used to indicate internationally collaborative research.

D.4 — Field definition and data validation

In the interim stage we conducted an exercise to test the validity of the approach used to identify publications related to RAI in extreme environments.

The following process was followed:

- First, a list of Hub researchers, facilitated by the UKRI team, and containing 215 different researcher names and affiliations was matched to their ORCID identifiers (where available, in ~11% of the cases). This preparatory step was undertaken to make sure that as many programme participants as possible could be unequivocally matched to their publication record.
- Second, the publication record for all these researchers (post-2017 publications) was extracted from the dataset. This resulted in a list of 1,217 unique publications. The study team performed a manual classification of their publications as being in or out of scope of the programme, by reading all the titles and abstracts of the publications. These publications were classified as being totally in scope (robotics in the extreme environments covered by the programme), in scope in terms of underpinning research in robotics that is generally needed to operate in unstructured environments (but with no direct link to applications in the extreme environments covered by RAI-EE), and not related (in areas explicitly out of scope of the programme, or not related to robotics/AI research).
- Third, the internal classification undertaken by the study team was checked and quality assured by an external expert (Prof. Dr. Bradley Nelson from the Multi-Scale Robotics Lab in ETH Zurich). The expert checked again a random sample of 250 papers (20.5%). The conclusion of this classification exercise is that the classification had a false positives error of 7.9% and a false negatives error of ~12%. Assuming that misclassifications were evenly distributed and that the classification by the expert is error-free, this means the classification underestimates the number of publications that are in scope by around ~4%. In practical terms, the classification error would be even less as all the 250 papers classified by the expert were incorporated into the classification that the study team had performed.

Table 26 gives an overview of the hub researchers published output post-2017, and its relevance to the RAI-EE programme.

Table 26 – Results of the quality assured classification of publication output from Hub researchers
Source: Publication output of 215 researchers involved in the Use-inspired Research Hubs. Technopolis and Prof. Dr. Bradley Nelson from the Multi-Scale Robotics Lab in ETH Zurich (2020).

Classification	Number of publications (post 2017)
Research directly in scope of RAI-EE (i.e. where the application to extreme environments in scope is mentioned in title or abstract)	220 (18%)
Underpinning research useful or necessary for RAI-EE	380 (31%)
Not related to RAI-EE	617 (51%)
Total publication output of 215 researchers involved in the Use-inspired Research Hubs	1,217 (100%)

There were two main takeaways of the validation exercise. First, RAI-EE research is challenging to identify via keywords and there is a very fine balance between accuracy and recall whenusing such techniques. Every additional keyword that is added with the objective to capture as many publications in scope as possible introduces the possibility of increasing false positives (e.g. marine research using UAVs as a tool to collect samples close to underwater volcanoes). While the expert classification is always more accurate, the keyword approach is the only feasible approach to scan all the scientific literature internationally to provide country-level comparisons and metrics.

Additionally, as shown in Table 26 for each paper that is fully in scope of RAI-EE, Hub researchers produce 1.73 publications with robotics and AI research that underpins it, but may not yet be directly related, to the scope of the programme. This can be because the research is more abstract or lower-TRL, but still tackles issues that one needs to solve in order to develop RAI-EE solutions.

Appendix E

Stakeholder interviewees

Mark Gascarth
EPSRC – Head of Digital Security and Resilience

James Dracott
EPSRC – Head of AI and Robotics

Tony Forsythe
UKSA – Head of Space Technology

Sue Horne
UKSA – Head of Space Exploration

Nikos Pronios
Innovate UK – Innovation Lead

David Bisset
Founder – Itechnic

Paul Clarke
Robotics Growth Partnership – Co-chair

Andy Cunningham
QinetiQ – Capability Development Lead

Phil Williams
KTN – Head of Robotic Systems

Peter Collinson
Dendrityca – Founder

Get in touch:

Asha Easton,
asha.easton@iukbc.org.uk

iuk-business-connect.org.uk

Innovate UK Business Connect