Using the ‘Internet of Things’ to Support Dynamic Risk Assessment in Future Concepts of Operation for Air Traffic Management

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Abstract. The ‘Internet of Things’ focuses on the introduction of software into any artifact that is not usually computerized or more generally on the digital representation of physical objects across distributed networks. Much of the hype surrounding these concepts has centered on mass consumer devices especially, in home automation and transport logistics, for example making the contents of a fridge discoverable from a mobile device. In contrast, this paper uses concepts from the Internet of Things to inform the dynamic risk assessments that can guide future concepts of operation in Air Traffic Management. In the past, most aerodromes have relied on linear approaches using conventional Instrument or Microwave Landing Systems (ILS/MLS). These linear approaches have advantages; they enable crews to learn how to stabilize and execute landings. However, there are numerous disadvantages. Static linear approaches are often based on risk assessments for ground infrastructure that are seldom updated and often do not reflect changes in the local population. They are inflexible and cannot easily be altered in response to changing meteorological conditions. Static linear approaches are also often poorly designed in terms of the impact that noise has on the local population and, in consequence, there are tight controls on the number and timing of departures/arrivals. In contrast, we show how information about the distribution of the population and ground infrastructures can be used to optimize approaches for a range of local conditions. A mass of detailed data, for example about the movement of people at different times of the day, can easily be obtained using standard information retrieval techniques. This data can then be used to minimize the risk to the ground population and the environmental impact from aircraft noise. The development of Ground or Satellite Based Augmentation Systems provides the opportunity to tailor vectored approaches using up to date information about the distribution of ground based infrastructure or in response to changing meteorological conditions rather than relying on the often obsolete, static risk assessments that have informed linear approaches. This argument is supported by a range of tools that draw on local population data to assess the risks of debris for ground-based infrastructures and the impact of aircraft noise. These assessments are informed using data gathered from data about the physical objects and about the local populations under vectored approaches, providing one example of a more general opportunity to use concepts from the Internet of Things in flexible and creative ways to inform the development and operation of safety-critical systems.

1 Introduction

The 'Internet of Things' focuses on the introduction of software into any artifact that is not usually computerized or more generally on the digital representation of physical objects across distributed networks. Much of the hype surrounding these concepts has centered on mass consumer devices especially, in home automation and transport logistics. In contrast, this paper uses concepts from the Internet of Things to inform the dynamic risk assessments that can guide future concepts of operation in Air Traffic Management.

1.1 Static Risk Assessments and Conventional Approach Procedures

Spriggs [1] has argued that runways are interfaces to the Terminal Area of airspace comprised of Standard Arrival Routes (STARs) and Standard Instrument Departures (SIDs). Within a Terminal Area, two types of instrument-based approach are used to land aircraft. Non-precision approaches use conventional navigation tools, such as the VHF Omnidirectional Range (VOR) system, to bring aircraft to a point where the pilot can perform a visual landing. The pilot lands without vertical guidance using a series of steps or descents down to the ground. However, controlled flight into terrain (CFIT) accidents occur more often during non-procedural approaches. In contrast, Instrument or Microwave Landing Systems (ILS/MLS) support precision approaches with lateral and vertical guidance on stabilized continuous descents. In other words, aircraft follow what can be thought of as a beam down to the runway. This offers numerous advantages. Aircrew become familiar with a small number of predefined approaches over time – they gain confidence in stabilising the aircraft in a range of meteorological conditions and become proficient in following ATM instructions down to the runway.

The static nature of conventional linear approach procedures raises a number of concerns. ILS/MLS infrastructures are expensive to maintain and calibrate. In consequence, a risk assessment is created before an approach is approved and the infrastructure is deployed. Operators will consider the hazard that aircraft pose for the population on the ground and to any associated critical infrastructures [2]. These risks were illustrated by the crash of El Al Flight 1862 when a Boeing 747 cargo plane collided with high-density flats in Groeneveen close to Schiphol airport killing 4 crew, 39 people on the ground. This remains the worst aviation accident in the Netherlands.

Existing pre-defined ATM vectors for ILS/MLS landings are designed to ensure separation; to improve the flow of aircraft; to reduce the impact of noise on the local community; to avoid areas of known hazardous, to minimize impact of local weather patterns etc.

The costs of making any change mean that STARs and SIDs are seldom changed. In consequence, the associated risk assessments can become obsolescent through changes in the local population density, especially when planning authorities do not always consult aerodrome operators when approving new applications [3]. In many cases, Terminal Area risk assessments stretch back decades to the time when an aerodrome was first constructed. In other words, the static linear nature of conventional instrument approaches mean that there is no incentive to revise the underlying safety case unless explicitly requested by national regulatory authorities. However, future concepts of operation in Air Traffic Management create a need for more dynamic and flexible approaches.

1.2 Future Concepts in Aircraft Approach Procedures

The development of Ground and Satellite Based Augmentation Systems (G/SBAS) provide alternative infrastructures, these enhance GPS to meet acceptable levels of integrity, continuity, availability. In terms of safety, increased (vertical) accuracy and integrity means that it is possible to lower the decision height before which a landing must be accepted. The use of satellite infrastructures also helps regional airports that are not equipped with MLS/ILS to reduce the risk of CFIT. As a result, the International Civil Aviation Organization (ICAO) has encouraged all instrument runways to provide approach procedures with vertical guidance by 2016.

The use of G/SBAS provides further benefits because aircrews are not restricted to the linear approaches characterized by conventional ILS/MLS infrastructures. Satellite positioning can, in theory, offer greater flexibility in terms of the vectors used during approach and landing. However, this raises a number of safety concerns if a Terminal Area controller were to direct aircraft to fly over areas with a high population density or over critical infrastructures. One solution would be to extend existing techniques – to conduct a more sustained survey and risk assessment of the zones around an aerodrome. However, this increases the likelihood that any risk assessment would be rendered obsolete through changes in population density and urban development. In contrast, this paper describes the development of dynamic risk assessment techniques that support more flexible G/SBAS approaches. We have exploited information retrieval tools using concepts from the Internet of Things to ensure accurate and up to date information about hazardous ground infrastructures and local population distributions. The intention is not only to minimize risk but also, for example, to minimize the noise impact of aircraft operations on the local community. We can vector approaches to reflect changing population densities or meteorological conditions at different times of the day. The approaches can also be tailored to meet specific short-term restrictions, for instance at times when large crowds attend sporting events.

2 Dynamic Risk Models

This project stemmed from work to estimate the impact that debris might have on the population living under an approach. The first component of the software architecture was a debris model. These models calculate the motion, impact location and volumes of airspace affected by falling objects, for instance following a mid-air collision or break-up [4]. Debris models use mathematical abstractions to calculate the interactions between gravitational forces, lift and wind velocity. Previous examples include the TAP (Trajectory Analysis Program) [5]. This relatively simple tool is in the public domain and can be easily ported to support a wide range of research projects. TAP models the initial altitude of an aircraft; altitude of impact at ground level; wind velocity and direction; horizontal true airspeed at disintegration; rate of climb or sink at disintegration; the weight of the projectile; the projectile drag coefficient; projectile frontal area. It estimates the horizontal distance from disintegration at impact; the horizontal, vertical, and total velocities; terminal velocity; the flight-path angle at impact and the ground speed of the projectile at impact including the x and z components of that velocity. For example, the motion of falling debris is opposed by *aerodynamic drag*. This mechanical force is generated by the difference in velocity between the solid fragment and the gaseous atmosphere:

$$\mathrm{F}_D = \frac{\mathrm{pv^2C}_D\mathrm{A}}{2}$$

F_D is the drag force, p is the mass density of the gas or fluid, v is the velocity of the object relative to the gas or fluid, A is the reference area, C_D is the drag coefficient. *Lift* is a force, which occurs when a moving flow of gas is turned by a solid object. Following Newton's third law of motion the flow is turned in one direction and lift is generated in the opposite direction, perpendicular to the debris' direction of motion:

$$\mathrm{F}_L = \frac{\mathrm{C}_L\mathrm{Apv^2}}{2}$$

C_L is the lift Coefficient, A is the surface area of the debris, p is the air density, v is the velocity of the debris. The lift force generated by a piece of debris is directly dependent on the debris' shape. For example; a flat object, such as a portion of wing will generate a larger lift force when compared to cube shaped debris. A larger lift force will result in the debris having a slower velocity. Therefore the wing will fall more slowly than the cube. Each fragment of debris has an initial state vector which is represented by a position and velocity. An initial state vector might be altered in particular simulations to model the velocity that results from an explosion. In addition, the trajectory for a piece of falling debris is mainly defined by its *Ballistic Coefficient*. This can be calculated as:

$$\beta = \frac{\mathrm{W}}{\mathrm{C}_D\mathrm{A}}$$

W is the weight of the debris fragment, C_D is the drag coefficient, A is the representative area used to calculate the drag coefficient. The ballistic coefficient represents the weight to drag ratio. Objects with a low coefficient fall more slowly. The lower the β value then the greater impact *wind velocity* will have on the trajectory of an object.

3 Modelling the Impact of Debris from Commercial Aviation

Previous debris modelling tools that support aerodrome design and operation use stand-alone architectures [6]. The user must manually enter relevant data about meteorological conditions, about aircraft characteristics and about ground based infrastructures. This is time consuming and error prone. Further concerns stem from low fidelity terrain models; most existing tools lack the features associated with Geographical Information Systems (GIS). They do not provide information about specific buildings, about the activities conducted in them or about the people living and working there. In contrast, we chose to base our implementation around a web services model so that we could draw on live data from a number of different applications [7]. In particular, the following pages describe how our tools extend information retrieval techniques based on concepts fro from the Internet of Things to derive dynamic data about:

- Real-time flight data based on an ADS-B server.
- 3D terrain model based on an existing GIS;
- The local built environment, including schools, factories etc;
- Critical infrastructures, including local major hazard sites;
- Local population densities;
- Live and archived 24/7 meteorological data, including wind speed;
- An aircraft noise model – interacting with terrain/built environment.

Federated information architectures are common in many areas of mass-market computation, for example flight-scanning services integrate live price and scheduling data from many different airlines. However, they have not been widely used to support the development of safety-critical applications. One reason for this is the difficulty of ensuring the validity of data from distributed information sources. In consequence, we cannot simply use public data derived over from Internet sources in an ad hoc manner – the use of integrated data services does not remove the requirement to validate the information used to inform our dynamic risk assessments. However, our use of a modular, distributed architecture offers great flexibility as common interfaces help us to choose between data from a range of different sources. There are minimal overheads associated in substituting more reliable data servers should doubts be concerned about an existing source

3.1 Integrating Live Flight Information

The first attempt to exploit concepts from the Internet of Things to support more dynamic forms of risk assessment focussed on integrating the TAP debris model with live flight data, in particular using Automatic Dependent Surveillance – Broadcast (ADS-B) servers. Aircraft use the ADS-B protocol to send out updates on their velocity and position at least once every second. In order to do this, they use a range of on-board equipment, including enhanced GPS receivers. At present ADS-B is optional, however, it is likely that most commercial aircraft will be required to carry this equipment following the implementation of the NextGen and SESAR initiatives. The use of this technology avoids the overheads associated with the maintenance of ground based radar systems and offers increased accuracy in areas of sparse coverage by conventional radar infrastructures. The chosen server provided a standard API for real-time access to live data on aircraft across 45 countries. The server integrates information from another 50 independent sources covering both private and commercial traffic. A limitation of this aspect of our implementation is that there can be delays while the simulator loads flight plan and trajectory information across busy areas of airspace – for instance above major hub airports. However, each run of a simulation can be cached for later replay. The development of a generic API supports the substitution of alternate servers or the integration of multiple data sources in future versions of our simulator. Figure 1 provides the resulting interface – this enables users to trace the impact of debris or of a CFIT on ground-based infrastructures using live traffic patterns. The camera position has been deliberately composed to show traffic across the South-East of the UK – subsequent figures show the application of this approach to Terminal Areas.

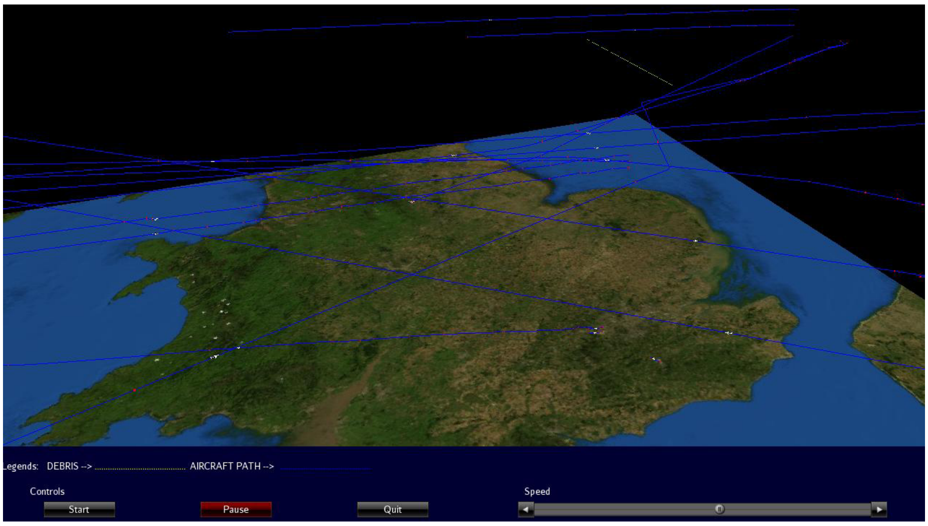


Fig. 1. Integrating of ADS-B and Debris Models (Ack: Marco Sarconi)

3.2 Integrating Terrain Data and the Built Environment

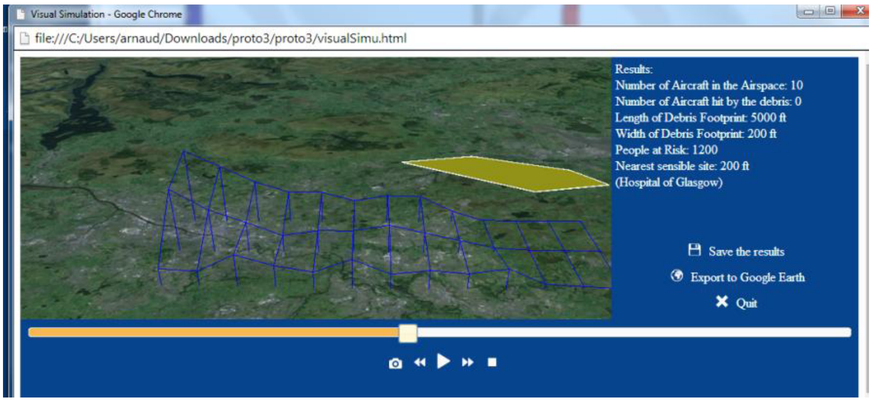
Figure 1 also illustrates our use of three-dimensional satellite imagery and a mapping service to support the visualisation of dynamic risk assessments. Users can trace the four-dimensional trajectory of flights as they pass across particular volumes of airspace. They specify the coordinates and altitude that they wish to view and the aircraft are presented against a background that can include cartographic details or photographic representations of the ground at a number of different levels of resolution. This is important when assessing the impact of debris from any mid-air collision on ground based structures or population centres. A limitation of the present implementation is that the servers we use will provide access to photographic and cartographic tiles that then have to be 'stitched together' in our visualisation. In the future, the modular approach might be used to integrate more general GIS tools.

3.3 Integrating Population Data and the Built Environment

The next area of integration focused on local population densities and on information about the built environment, including critical infrastructures. In previous work, we have described the use of the UK Government's National Fire Service Emergency Cover (FSEC) Toolkit to inform risk assessment [8]. This gathers census data together with information from local fire safety inspections to provide data about the location and usage of almost every building in the UK. Its original purpose was to enable government to ensure that the deployment of emergency services mirrored changes in demographics. This provides ideal data for the development of a dynamic risk assessment tool for flexible approaches under future concepts of operation in ATM. However, it holds confidential information and is designed as a stand-alone application without a web-service interface. Governments around the world are increasingly using open data initiatives to allow citizens access to key national statistics. The Statistics and Registration Service Act 2007 has promoted the production and publication of official statistics in the U.K. As a result there is free access to many data sets that include accurate and comprehensive population estimates [9]. However, different national census servers implement a range of different interfaces. Although they arguably provide the most accurate national data, they cannot yet match the global coverage that has been achieved by the other elements of our toolset.

A number of alternate population data sets and tools are available with varying degrees of coverage, accuracy, accessibility, and cost. LandScan integrates a range of data sources to estimate population densities. These include government census returns, using administrative boundaries. It also uses the automated analysis of satellite imagery to estimate distributions by determining land use – for example, distinguishing between asphalt and vegetation, high-resolution imagery is used to identify settlement patterns and building characteristics. The result is a global population distribution with 1km resolution [10].

The Gridded Population of the World provides a raster model for global population data based on a cell resolution of 2.5 arc minutes square. GPW represents a compromise – global coverage is achieved but at the cost of the finer granularity available in government sources of statistical data. Hence, in our toolset we the GPW as a first approximation that enables us to rapidly model Terminal Areas from around the globe. We can then gradually refine the population data as more detailed sources are identified. Figure 2 illustrates the resulting interface the open mesh illustrates the population density superimposed on the satellite ground imagery. The smaller filled mesh illustrates the debris field descending to the ground. The image also illustrates how our toolset includes critical infrastructure data – in this case we have superimposed the local motorway network. Following the principles presented in this paper we could also include live data about traffic patterns – this remains an area for future work.



Results:
Number of Aircraft in the Airspace: 10
Number of Aircraft hit by the debris: 0
Length of Debris Footprint: 5000 ft
Width of Debris Footprint: 200 ft
People at Risk: 1200
Nearest sensible site: 200 ft
(Hospital of Glasgow)

Fig. 2. Integrating Population and Infrastructure Data (Ack: Arnaud Prouzeau)

3.4 Integrating Meteorological Data

Previous sections have explained how debris-modelling tools rely on meteorological information to trace the impact of wreckage for the ground population. This arguably poses the greatest challenges to our design. There are few reliable sources of live wind speed data in commercial airspace. Most Air Navigation Service Providers rely on forecasts that are seeded by data from radiosonde balloons released well away from any air traffic. A number of servers now provide live access to this extrapolated data and have been integrated into our tool set. This illustrates the further benefits that can be derived from the use of an open architecture for dynamic risk assessment software. The limitations of extrapolated meteorological data are being addressed by a number of national and international initiatives. For example, the US National Oceanic and Atmospheric Agency (NOAA) provides public interfaces to Aircraft Meteorological Data Reports using Aircraft Commications Addressing & Reporting. These servers report live meteorological observations from aircraft operated by a host of airlines including Alaska, American, Delta, Federal Express, Southwest etc. Again, however, there do not seem to be international agreements on the formats to be used across similar initiatives in different parts of the globe.

3.5 Integrating Aircraft Noise Models

Previous sections have explained how we have extended design concepts from the Internet of Things to support the development of safety-related software. In particular, we have integrated digital representations of physical objects to inform dynamic risk assessments for future concepts of operation in Air Traffic Management. An additional motivation is that previous consumer applications of these techniques have supported a range of different applications using the same information infrastructure. In this case, we have extended the safety-related focus on debris modelling to consider the environmental impact of aircraft noise. Rather than using the TAP abstractions to develop a debris field, we have extended existing noise modelling tools to calculate 3D intensity maps of the noise emitted from aircraft in the vicinity of airports. In general terms, aircraft noise stems from the engines and the body. Engines fans emit across a range of spectral frequencies. Compressors also have a significant but lesser impact. The shape of the fuselage and the wings can also influence the distribution of noise generated by an aircraft. It will also be influenced by the angle of descent/ascent – given that the ground can absorb up to 12db. Noise models are further complicated by attenuation as the signal diminishes with distance from the source in both the longitudinal direction of travel and lateral directions. All of these factors interact with the built environment – different architectural features will affect noise attenuation. There are also a host of human perceptual and physiological factors to be considered in noise modelling. Finally, it is important to recognise that the sound quality varies with the phase of flight and by flight crew actions, for example when the pilot drops the throttle at the end of a climb or when the landing gear are lowered. There can be differences of between 60-100db for different operating procedures to achieve similar outcomes – for example by varying the rate of climb.

A number of existing noise profile/contour models already exist [11]. For example, the UK CAA have developed an accurate representation of the impact on an area some 80 km by 50 km around Heathrow. This is derived from the UK Civil Aircraft Noise Contour Model ANCON [12]. The data from this system is calibrated using Noise and Track Keeping System (NTK) microphones around major airports. However, ANCON does not provide a web service interface. It is an extremely valuable legacy application tat the CAA intends to redevelop in the medium term. Until this is done, we were forced to implement our own simplified noise modelling system that lacks many of the features provided in the CAA's standalone system.

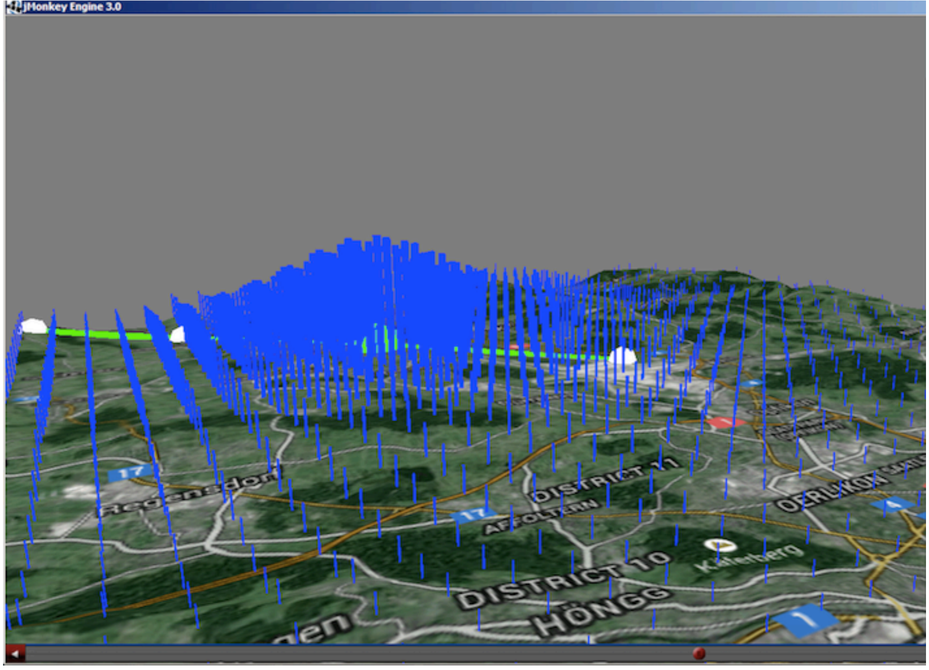


Fig. 3. Integrating Aircraft Noise Models (ack: Michael Roddy)

4 Conclusions and Further Work

This paper has used the design philosophy behind the Internet of Things to support dynamic risk assessments for future concepts of operation in Air Traffic Management. In particular, we have created a suite of integrated services that can be used to assess the risks associated with the more flexible, vectored approaches that are supported with the gradual transition from conventional ILS/MLS based approaches to those informed by the new generation SBAS/GBAS infrastructures.

We have integrated an implementation of the existing TAP debris modeller with real-time flight data based on an ADS-B server, with 3D terrain models based on an existing GIS, with data on the built environment, including schools, factories etc and critical infrastructures, derived using information retrieval techniques that are tailored to particular locations. Our tools integrate live and archived meteorological data, including wind speed, surface pressure and temperature. We have also extended this approach to capture information about population densities. An important strength of our approach is that we can simulate the impact of debris on flights in real-time and can rapidly configure our tools to assess the risks associated with aerodromes around the globe. In the past, it took many weeks to configure stand-alone models with significant associated costs. The flexibility of this approach has also been demonstrated by further extending the safety-related application of these tools to model the dynamic impact of aircraft noise.

A number of concerns remain about our use of Internet-based information servers. The integration of public data sources does not remove the requirement to ensure validity and consistency. However, our use of a service-oriented architecture supports the substitution of alternate sources and models as more accurate models are identified, for instance the NOAA AMDR meteorological data or the CAA ANCON revision.

The approach described in this paper opens many areas for further work. During our validation studies, aerodrome operators identified opportunities to integrate more diverse hazards into our 3D risk visualisations. In particular, the existing models might be extended to capture the risks associated with wildlife distributions on particular approaches. Traditional safety assessments have been based on costly and infrequent surveys that are specifically commissioned by aerodrome operators. They seldom exploit the annual results of national public surveys such as the UK Royal Society for the Protection of Birds BirdWatch programme or the North American Breeding Bird Survey, both of which are accessible at different levels of resolution over the Internet.

This paper has emphasised the need for safety professionals to be more creative in the information sources that inform dynamic risk assessments. However, we have also identified wider opportunities – to reuse safety related information architectures to address environmental concerns. We have only started to identify the opportunities for further work. In terms of the noise modelling research, predictions derived from our tools can be used to simulate the impact of different approach procedures. Aircrews and ATCO can hear what local residents will experience.

The aim is to promote better 'behaviour', for example in terms of throttle control.

A more immediate application area includes the use of our integrated safety and environmental modelling tools during public enquiries that precede runway development. We can simulate the hazards and also the noise impact for aerodromes that have yet to be built. This further blurs the distinction between physical and virtual worlds in a manner that is entirely consistent with the ideas behind the Internet of Things.

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