Enabling autonomous take-off and landing in urban environments

Automotive Sensors in Hybrid Navigation Systems

Continental Engineering Services

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Executive Summary

The number of aircraft operations in unprotected, unpredictable environments, such as in inner cities, will have to increase beyond the capacity of traditional helicopter operations if the tremendous economic growth potential resulting from an advanced air mobility (AAM) infrastructure is to be realised. This makes automated systems for air traffic management key enablers of AAM-driven economic growth.

A cornerstone of air traffic management in cities is the ability of an aircraft to safely take-off, navigate and land in a complex urban environment even when communications, navigation and surveillance are degraded or lost, either in a distress scenario (e.g., an emergency aboard the aircraft) or an operational scenario (e.g., where the aircraft is deployed in response to a medical evacuation request, critical goods delivery, or simply convenient transportation).

To create an autonomous flight control system for safe operations in complex, urban environments, we studied the feasibility of a hybrid navigation solution implementing a detect and avoid function based on automotive sensor technology. We then studied ways of integrating such a system with passive ranging in 5G networks and traditional GNSS receivers.

We also look at the current and expected regulatory environment and present flight test results acquired in 2022 that confirm the validity of the approach.

Results demonstrate that a hybrid navigation solution based on publicly available networks and automotive sensors designed for autonomous driving is technically feasible and economically desirable. Based on these findings, we defined a possible development roadmap from proof-of-concept to operational readiness.

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Context and problem statement

The benefits of advanced air mobility

A recent study published by ADS[1] forecasts a global market potential for advanced air mobility (AAM) of between US$ 12 Billion to US$ 600 Billion annually by the mid-2030's.

The study evaluated several market analyses across consulting firms, investment firms and future air mobility companies. While the variation between the various pessimistic and optimistic scenarios is considerable and depends mainly on the extent to which regulators, standardisation bodies and infrastructure providers can keep up with the growth in demand, even the most pessimistic outlook represents a desirable business case.

AAM also offers a significant potential to stimulate economic growth and increase the capacity of our existing urban infrastructure. In addition to the commercial prospects, the development of AAM systems with low emission aircraft will also be an important step in the decarbonisation of regional air transport[2], creating a more efficient and sustainable air transport network. This makes AAM for urban and regional transport almost universally desirable, and a key element of future economic growth.

Like railroads, the automobile, aviation, and the Internet, AAM offers the potential to create a whole new economy which in turn has the potential to significantly improve the way we commute, network, spend our leisure time and perform our work.

Investing in technological developments that bring this change about is therefore key to unlocking this future potential.

The importance of autonomous take-off and landing capabilities

The considerable economic benefits of advanced air mobility as outlined above are constrained by the ability of AAM services to scale with the demand generated by the economic growth of a free and unconstrained market.

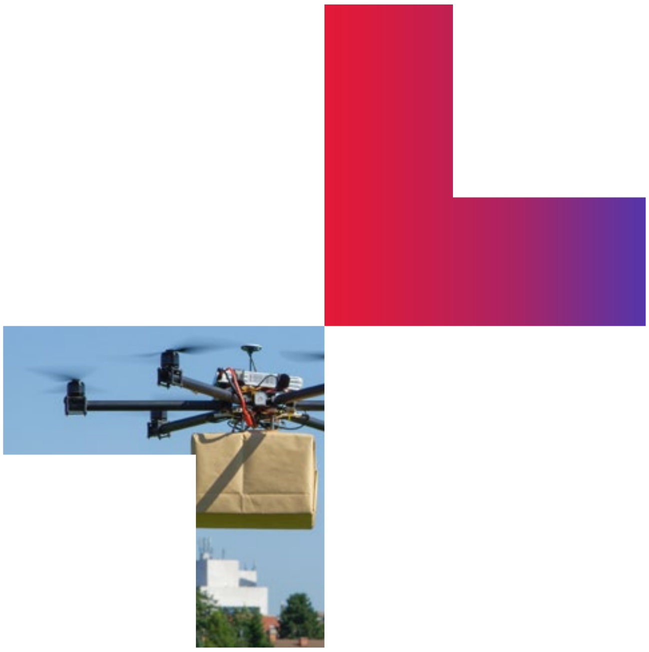
In most routine civil aviation operations today, operational reliability and safety is achieved in no small part by providing protected environments in the air and on the ground. Aircraft take off from and land at fields which are mostly protected from the interference of uncontrolled traffic. From major airports to dedicated helipads, aircraft operations can therefore rely on a reasonably predictable environment. Where civil aircraft operate in uncontrolled airspace, primary responsibility is placed on their human pilots to detect and avoid hazards, whilst take-off and landing outside of airfields and heliports normally rely on ground personnel to identify and protect suitable operating areas. In all cases, specially trained pilots manoeuvre their aircraft with great care around obstacles and other traffic, relying almost exclusively on “see and avoid”. The necessity to provide such a protected environment limits the capacity of urban airspace and is one of the major reasons why urban air mobility is currently limited to helicopter services for VIP transports, sightseeing and emergency services.

Growing operations in urban airspace beyond our present-day helicopter services at an economically meaningful scale therefore requires new airspace concepts of operations, new technologies to enable them, and consequently new standards and regulations.

The growth in airspace capacity is limited by the technological progress that can be realistically achieved, and the capacity of regulators to keep pace. Because even in the most libertarian of markets, where economic growth tends to be fastest, transport services will still need to maintain interoperability and acceptable levels of operational reliability and safety.

While the regulatory and standards process is well under way, it has not yet produced sufficiently detailed requirements for future AAM systems to design them in great detail. However, following from the above, we can state with confidence that they need to provide, at the very least, a capability to safely land and take off in busy cities, surrounded by tall structures, regardless of weather, at levels of safety and security that are common for aviation today. To achieve this, service providers and operators will need to avail themselves of aircraft equipped with resilient and reliable electronic conspicuity, cyber security and communication, navigation and surveillance systems.

A first-generation system might only need this capability in emergency scenarios, for example, when performing a precautionary landing while traveling between vertiports across town. However, the growth in airspace users required to support the economic growth figures widely expected[1] necessitates that, by the mid 2030’s, aircraft movements will have reached a level where landing and take-off operations in urban airspace have become routine.



Developing urban airspace navigation technologies that allow take-off and landing in complex environments with the operational reliability, the safety and the security that has generally been accepted for aviation is therefore a key enabler of AAM-driven economic growth.

Challenges

1 Complex environments

Environments outside controlled airspace, airports, heliports and vertiports can be considered as “complex” because of their relatively poor predictability.

Where air operations take place close to buildings, traffic separation is greatly reduced, and the environment is subject to a much greater rate of change. Poorly predictable objects such as cranes, flags, decorations, and drones are more likely to have an impact on AAM aircraft than on traditional aircraft. Even so, operations in such environments are desirable, as a key economic growth potential of AAM derives from the ability to provide fast and accessible urban transport outside the controlled environments of airports and helipads, and in the general urban environment. At the same time, current services enabling precision navigation, including Global Navigation Satellite Services (GNSS), Space-and Ground-based Augmentation Systems for GNSS (SBAS and GBAS) services, are greatly impaired in urban environments due to obstruction and multipath propagation effects in urban canyons, and their susceptibility to spoofing and jamming.

Emerging alternative urban navigation solutions, such as those based on 5G mobile signals[3] could mitigate the shortcomings of GNSS based navigation to some extent, but they may not provide full coverage of the AAM flight areas, nor will they address the need to deal with poorly predictable objects in the environment.

AAM aircraft therefore need to be able to precisely navigate this complex environment without the need to rely exclusively on traditional satellite navigation services and to be robust in the face of changes to the environment.

2

Standards and regulations

Whereas there are standards that govern functional safety in the automotive industry (see Page 9), there are currently no specific aviation standards that apply to the autonomous functions of advanced air mobility platforms. The closest relevant standards and regulations are those that govern Remotely Piloted Aircraft Systems (RPAS) which are many and varied (see Figure 1 below).

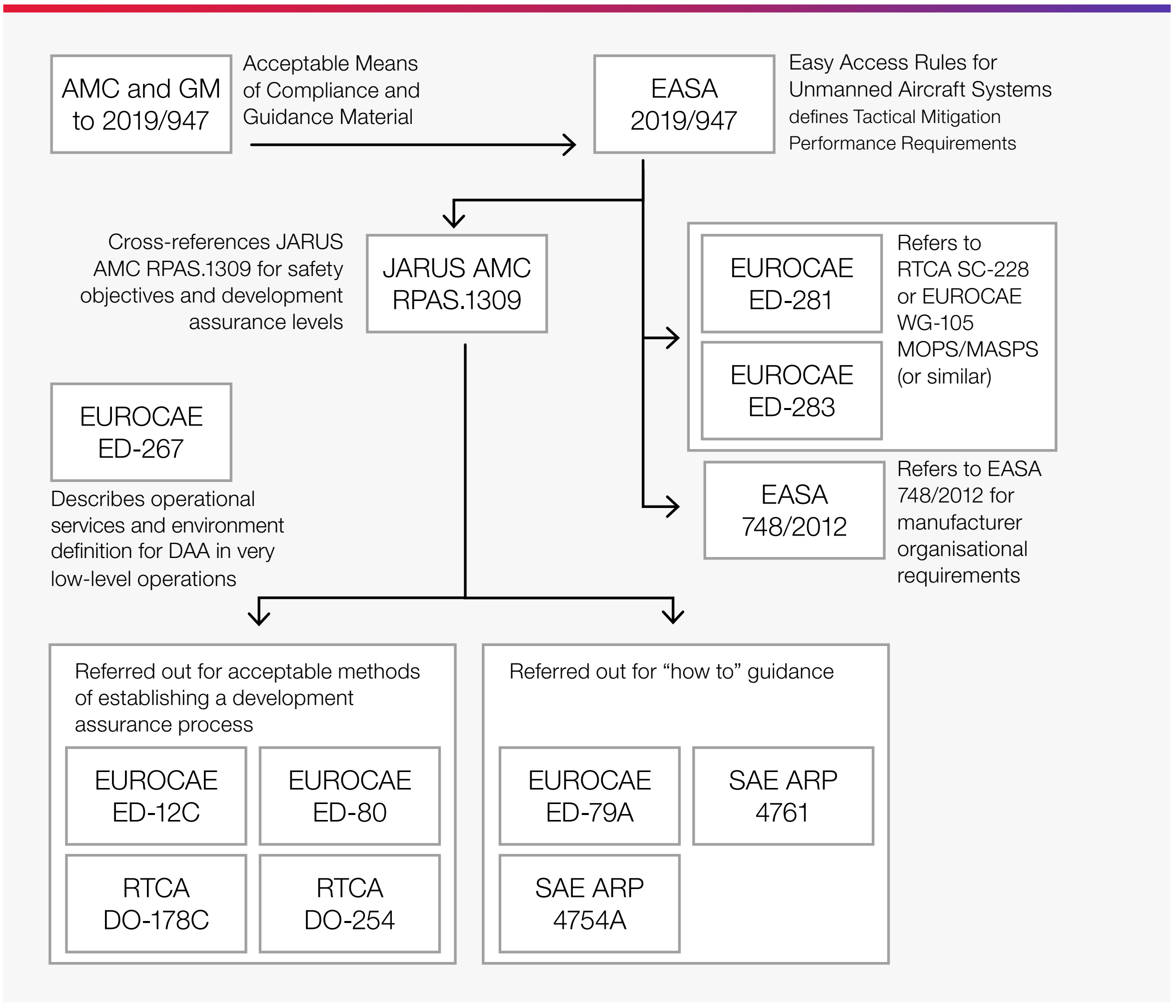


Figure 1: Document Map - standards and regulations governing Remotely Piloted Aircraft Systems (RPAS) with a focus on autonomous take-off and landing

EASA regulation 2019/947[4] details provisions for the operation of unmanned aircraft systems as well as for personnel, including remote pilots and organisations involved in those operations. This includes specification of Tactical Mitigation Performance Requirements (TMPR) and provides qualitative criteria for the different functions and levels of the TMPR. For environments where the collision risk is high, there is an expectation that the operator would be required to comply with recognised Detect and Avoid system standards such as those in ED-283[5].

EUROCAE document ED-283, the minimum aviation system performance standards for RPAS Automatic Take-Off and Landing (ATOL), defines the basis for assessing and establishing operational, safety, performance, and interoperability requirements for ATOL. The scope of this particular document is limited to fixed-wing systems operating in non-segregated terminal areas and airfields of up to medium complexity, albeit under Instrument Flight Rules and in different meteorological conditions without visual assistance of the Remote Pilot. The key system requirement, SPR#9010, is that the ATOL capability for RPAS in the "Certified" category achieves an overall level of safety at least equivalent to the one required for the corresponding manned operations without negatively affecting the current Air Traffic Management system, such as reductions in capacity or safety margins.

EASA 2019/947 also cross-references JARUS document AMC RPAS.1309[6], where safety objectives and Development Assurance Levels (DALs) for airborne software and electronic hardware are defined. It also specifies the relationship between RPAS class and Complexity Level and the associated Severity of Failure Conditions, Allowable Quantitative Probabilities and Development Assurance Level for Software and Complex hardware, required to maintain safe flight and landing to that of equivalent manned aircraft (excluding loss of safe separation). At RPAS functional level, no single failure will result in a catastrophic failure condition. JARUS AMC RPAS.1309 recognises various standards as acceptable methods for establishing a development assurance process for aircraft, systems, software, and airborne electronic hardware for all classes of RPAS. These include the Society of Automotive Engineers (SAE) Aerospace Recommended Practices (ARPs) 4754A[7] for a more broadly applicable definition of the DALs and 4761[8] for the Functional Hazard Assessment process, and EUROCAE standards ED-12C[9] and ED-80[10] which define the design assurance objectives that must be accomplished for given DAL for airborne software and electronic hardware respectively.

3

Operational safety

Whatever the forthcoming standards and regulations will look like, we can already state that that they will very likely require certifiable operational safety of a similar level than we are currently achieving in commercial aviation. Outside of emergencies and outright armed conflict, we cannot reasonably conceive a set of circumstances consistent with our free-market economy and democratic governance under which anything less would be acceptable. We can therefore look to existing agreements, standards and guidance by the International Civil Aviation Organization (ICAO), EUROCAE, RTCA and others to derive reasonable assumptions about operational safety requirements.

4

Security considerations

Any system designed to ensure the operational safety of airborne vehicles must necessarily take security considerations into account. For example, there have been many well documented examples of GNSS spoofing – including cases where British vessels were accused by hostile governments to have illegally sailed through their territorial waters, when in reality they were in port miles away[11]. Such spoofing of navigation signals is no longer reserved for sophisticated intelligence services of hostile governments attempting to provoke confrontation – it is easy and cheap enough to be executed by an individual with sufficient skill and knowledge about where the necessary hardware can be procured[12].

Jamming technology is even more straightforward to acquire through Internet suppliers, and studies[13] show that the illegal use of such equipment is likely to be becoming ubiquitous. Even in cases where the aircraft is not the target, the area of effect of such devices is often sufficiently wide that any receivers in the vicinity will be subject to jamming.

These threats, malicious or inadvertent, are likely to be most prevalent in urban cityscapes where the protected environments of airports cannot be practically reproduced. We must therefore take into account that more individuals with less screening will get closer to aircraft than in a traditional aviation environment.

Modern GNSS signals, such as Galileo Open Service Navigation Message Authentication (OSNMA), are starting to incorporate features which support secure navigation. However, a secure navigation system such as the subject of this whitepaper must be able to make autonomous assessments of its sensor data, and diversity will be the key to this goal. Multi-constellation GNSS guards against the systematic failure of any one GNSS constellation; alternative positioning sources on other frequencies (such as 5G), or that are internal to the vehicle (such as inertial sensors), provide resilience against jamming or spoofing; and situational awareness sensors such as radar, LIDAR and visual odometry provides fallback when all else fails, as well as precise local navigation.

Automotive sensors in hybrid navigation for advanced air mobility

Automotive standards for autonomy

Autonomous driving and autonomous flying in urban environments share very similar requirements and the underlying navigation principles are the same: “Sense, Plan, Act”. Autonomous flight can, therefore, be achieved using a similar approach to that of autonomous driving, exploiting sensors and systems which are widely available, proven for use and relatively inexpensive. However, standards and approaches to safety differ.

Functional safety features form an integral part of each automotive product development phase, ranging from the specification, to design, implementation, integration, verification, validation, and production release. To see how easily sensors and systems designed against these standards can be certified for use in aviation applications, we examine how well these standards map to applicable aviation standards.

The international standard for functional safety of electrical and/or electronic systems that are installed in serial production road vehicles (excluding mopeds) is ISO 26262[15]. The standard aims to address possible hazards caused by the malfunctioning behaviour of electronic and electrical systems in vehicles, in particular ISO 26262:

- Provides an automotive safety lifecycle (management, development, production, operation, service, decommissioning) and supports tailoring the necessary activities during these lifecycle phases.
- Covers functional safety aspects of the entire development process (including such activities as requirements specification, design, implementation, integration, verification, validation, and configuration).
- Provides an automotive-specific risk-based approach for determining risk classes (Automotive Safety Integrity Levels, ASILs).
- Uses ASILs for specifying the item’s necessary safety requirements for achieving an acceptable residual risk.
- Provides requirements for validation and confirmation measures to ensure a sufficient and acceptable level of safety is being achieved.

Hybrid navigation

A hybrid approach must be at the heart of any navigation system able to meet the safety and security requirements for advanced air mobility. By fusing the outputs of multiple sensor types, the weaknesses inherent in one can be mitigated by the strengths of another, resulting in a more accurate and reliable system.

Under good conditions, GNSS positioning can provide the foundation for very accurate positioning, particularly when combined with techniques such as precise point positioning and real time kinetic (RTK) positioning which make use of additional support data. However, in particular for RTK, convergence time as well as the need to receive data in real time can add latency to the positioning solution. This, depending on the speed of the vehicle, may inhibit timely decision making. Furthermore, environmental factors (such as multipath issues in urban areas) and malicious actions (such as jamming and spoofing) can limit both availability and reliability.

For short outages, an inertial measurement unit can provide continuity but, in the absence of absolute fixes, will lead to growing error and uncertainty in the position of the vehicle. These core technologies must, therefore, be combined with alternatives such as LIDAR, RADAR, visual odometry and 5G positioning. Safe navigation can be enabled through all round perception using such sensors. This can be achieved by considering the FOV coverage of these sensors in the system design phase.

Sensors in driver assistance and automated driving

Driver Assistance and Automated Driving systems in automobiles today make use of various sensing capabilities.

The higher the level of Autonomy (according to SAE levels) and the safety criticality of the vehicle functions the greater the number of sensors in such systems. These sensors include Narrow field of view cameras, Wide angled cameras, RADARs (short and long range), LIDARs and ultrasonic sensors, and may in the future be augmented by active RF signals.

The vehicle level functions are broadly classified into two categories – Cruising Functions and Low Speed Manoeuvring Functions. Typical cruising functions include Adaptive Cruise Control with Lane keep assist, Blind Spot Assist, Traffic Sign recognition for adapting to changing speed limits, Road curvature estimation for safe cornering, and Vulnerable Road User (Pedestrians, Bicyclists) detection. RADARs (Long and short range) and Long-Range Narrow field of view cameras are generally used for these applications.

In case of Low-Speed Manoeuvring functions like Automated Parking, Low Speed Collision avoidance, Traffic Jam Assist, Automated Emergency Brake, a combination of near field sensors such as Wide angled cameras and Ultrasonic sensors and short-range RADARs are used. In either case, information from different sensor modalities is fused using statistical and probabilistic methods to build better predictive models for the environment surrounding the vehicle.

Perception functions for autonomous driving

Complex systems that need to make critical decisions with high levels of Autonomy and minimal human intervention require a very high level of perception of the surrounding environment in which they operate.

Quite often such environments are very complex, extremely dynamic with similar systems or other human operated systems participating as well. This presents a plethora of challenges when developing perception functions for these systems. These challenges are not just limited to choosing the right set of sensors that are suitable for these use cases but also extend into making intelligent decisions as to how to combine and represent the data collected through these different sensors to support the autonomous decision making and route following functions.

There are several algorithms and techniques used to perceive the operating environment of an Autonomous Ground Vehicle. Especially in automotive applications a system relies on perception functions such as Object detection (Classical and Learning based), 3D reconstruction methods like Structure from Motion (SFM), Simultaneous Localisation and Mapping (SLAM) and Photogrammetry.

Having a segmented scene is crucial in gaining visual understanding of the environment in a machine vision context. A segmented image with various object classes is used as an input to the plan and act part of the automated driving stack. Key information such as the position of the lane markings with reference to the subject vehicle and presence of any vulnerable road users like pedestrians / cyclists is used to make decisions in path planning and manoeuvring.

Figure 2: Deep learning based semantic segmentation

Object detection capabilities involve segmenting the objects of interest in the image or other sensor data for instance from a RADAR or LIDAR using computer vision, image processing or other signal processing methods in the temporal or frequency domains. Recent developments in fields of Machine learning and Artificial Intelligence have paved the way for a much faster and accurate way of segmenting objects of interest like pedestrians, vehicles, and other static occupants in the scene. However, these methods are computationally quite intensive compared to their classical counterparts and in most cases have specific hardware requirements to run such models.

In automotive use cases, both low speed and high speed, 3D reconstruction methods are the key to understand free space in the environment. One example case is automated parking, where it is crucial to understand the availability of an open slot and dimensions of said slot to validate against vehicle requirements.

Methods like Simultaneous Localisation and Mapping (SLAM) aim to localise the autonomous vehicle platform in a 3D environment using various input data like GPS for positioning, vehicle odometry and Inertial Navigation Sensors (INS) for the attitude and heading information, camera input for visual understanding of the scene through distinct feature correspondences, RADAR, and LIDAR information for more accurate depth perception, while building a comprehensive model / map of the environment. For simpler applications where it is required only to understand the free space information, a Structure from Motion approach using cameras is employed. This method relies on establishing feature correspondences in a moving scene and further use these matching features to triangulate and localise them as 3D points in the world.

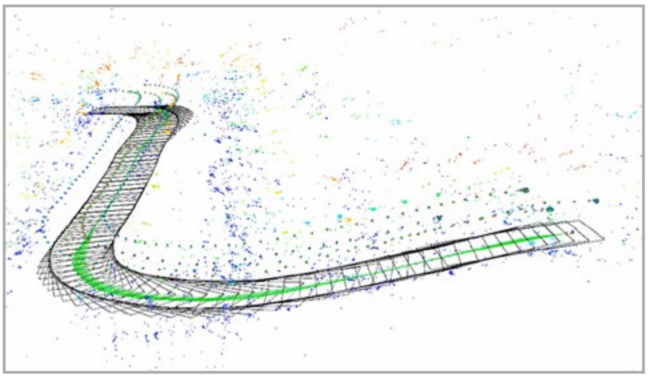


Figure 3: Map output from SLAM

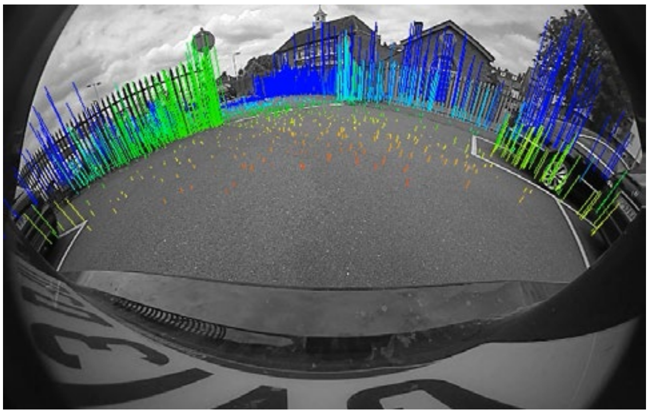


Figure 4: Static obstacle and free space information through SFM

Active sensors like RADAR and LIDAR are of great help in directly achieving a depth perception due to the nature of such sensors, but they lack the ability to give a contextual understanding of the scene which is in most cases important to make critical system decisions. For this reason, it is often preferred to fuse the sensor data from such active sensors with the visual information from a camera. To achieve an understanding of depth in image calibration of cameras with respect to the sensors and the operational frame of reference is required. Through calibration the 2D visual information can be transformed to achieve a 3D understanding of the scene.

The following data flow diagram depicts the high-level blocks of an autonomous ground vehicle. These blocks are categorised into functions that “Sense” the environment, functions that “Plan” the route / path based on a pre-programmed destination information or an end effect position of the vehicle, and functions that enable the vehicle to “Act”.

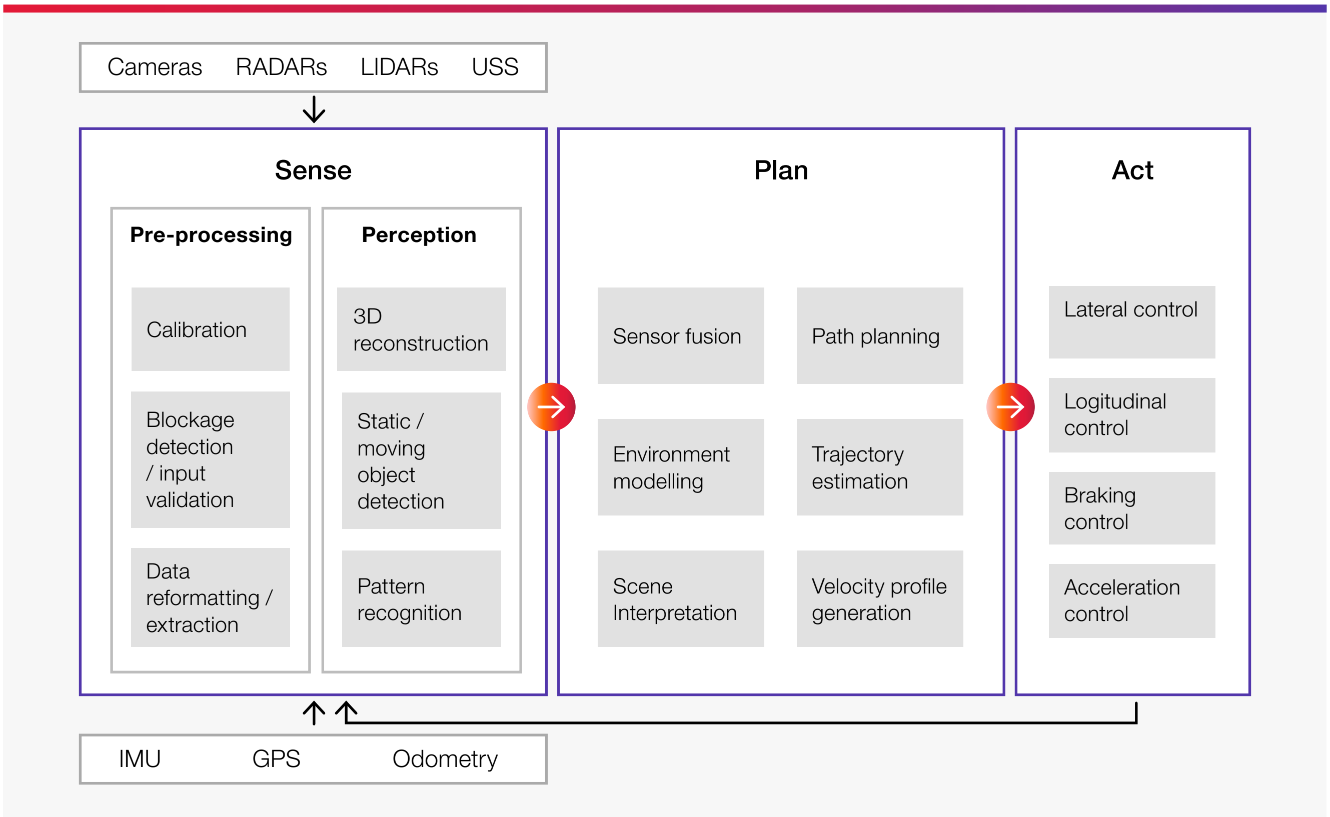


Figure 5: Data flows for an autonomous ground vehicle.

Very similar methods are prevalent in the present state-of-the-art autonomous drone navigation for various applications ranging from recreational videography to military reconnaissance. The principles of navigation for autonomous flying also boil down to the same “Sense, Plan, Act” model. With the addition of reliable altitude information autonomous flight can be achieved using a similar approach to that of autonomous driving.

Autonomous driving to autonomous flying

Given the similarity in working models, and data requirements to achieve sufficient understanding of the operational environment, similar functional blocks to that used for Autonomous driving systems can be applied to Autonomous flying systems.

Two key functions that we look to address in these systems using Automotive sensing capabilities are Safe Landing Zone Recognition and Obstacle Detection / Avoidance.

Safe landing zone recognition

In many nominal scenarios, landing zones will be well-defined and well-controlled areas where landing may be supported by dedicated local guidance technologies.

However, other scenarios are envisaged such as package delivery to arbitrary locations and emergency landings in a distress event. In these cases, while map data may be sufficient to identify a short list of potential landing zones, intelligent use of sensor data will be necessary in order to effect a safe landing. This will be especially true in non-designated landing zones and in areas with unknown characteristics (e.g., in an emergency when a known safe location can no longer be reached).

Automotive RADARs used for Adaptive Cruise Control type applications have a typical range in the order 0.1 - 300 meters. These sensors combined with visual information from a camera with sufficient Field of View can aid in achieving a good understanding of the terrain beneath a flight route which can be further analysed alongside map information to continuously look for potential landing zones in case of an unforeseen emergency. This can immensely increase the safety factor of both manned and unmanned flights instead of just relying on map, limited visual information and support from an air navigation service provider's (ANSP) air traffic control (ATC) service.

Obstacle detection and avoidance

An autonomous aircraft must maintain a model of the environment in which it finds itself. While in flight, this model includes other aircraft which must be tracked, meaning that their flight paths must be predicted. Some information may be available collaboratively through electronic conspicuity (e.g., ADS-B and related functions) but the vehicle will, in practice, be reliant on its own sensors (LIDAR, radar, visual odometry) to identify hazards and map its environment.

During the landing phase – especially when outside of a dedicated landing zone – the aircraft must be able to fly safely within a much denser environment where tracking will be extended to cover ground vehicles and pedestrians.

Whereas ground vehicles may be considered to operate in a broadly two-dimensional world, obstacle detection and avoidance for aircraft will need to take more account of hazards that may come into view from above or below. This introduction of a third dimension will impact both the positioning and selection of an aircraft's sensors and the processing required to construct a model of the surroundings.

Sensing in three dimensions can be achieved through a cluster of automotive wide angled camera sensors positioned strategically with the Fields of View covering all directions around the aircraft. This further benefits the system by having in some parts, an overlap in the FOV which can be used to achieve feature correspondence between views and also continuously track objects of interest across the views.

This extension into three dimensions is a key area of research, including the exploration of machine learning based methods to detect and localise objects of interest in the vicinity of the aircraft, especially during critical manoeuvres like landing and take-off.

Vision for autonomous landing and take-off

The following architecture is envisioned to address the Landing and Take-off operations of an Autonomous aircraft. Further analysis of various operational use cases, ODD (Operational Design Domain), distribution of DPT (Dynamic Pilot Task – Manual vs Automated), and MRC (Minimal Risk Condition) is presented.

Note: For the sake of readability, here on, "System" will be termed as "APS" (Auto-Pilot System)

APS Logical architecture

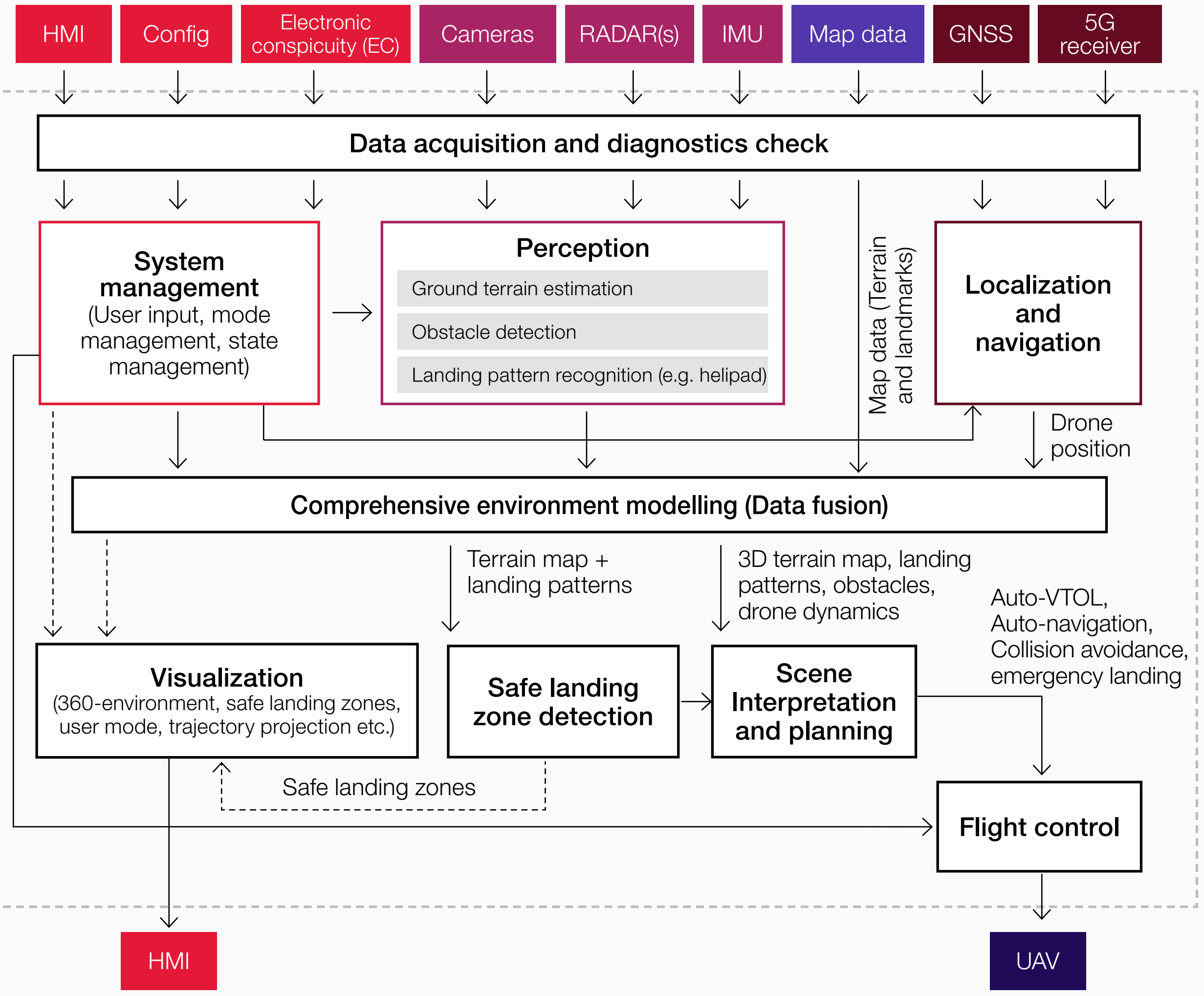


Figure 6: Auto-Pilot System logical architecture

User system interaction

Considering the logical flow of an APS, the following set of interactions are possible between the user and the system under various modes of operation and situations at hand (planned/ unplanned).

Enable/Disable APS
To engage/disengage the system an integrated HMI is used. In both enabled and disabled cases, the system shall run basic diagnostics (power, comm, sensors, software & hardware checks etc.) and set itself to Ready-and-standby (Enable) or to Shutdown (Disable).

Activate/Deactivate 360-EM
To activate/deactivate 'Sensing & Perception' functionality of the system to perceive 360-degree environment around the UAV, like – static obstacles, dynamic/ moving objects, free space, 3D terrain map, and Localization etc.

Activate/Deactivate Collision-Avoidance (CA)
To activate/deactivate evasive manoeuvre functionality to avoid collision with any approaching static/ dynamic objects in the path.

Activate/Deactivate SLZD
To activate/deactivate 'Safe Landing Zone(s) Detection' in case of an emergency landing where there is no designated landing area available (ex: Helipad)

Init Automated Take-Off/Landing
To initiate an automated vertical take-off/landing, where system shall perform a thorough 360-environment perception and check its capability for the expected functionality before confirming 'Ready'-ness to the user. This may apply in designated or non-designated landing areas, where the former may be expected to provide visual and/or electronic navigation beacons which would not be present in the latter case.

Activate/Deactivate Auto-Nav
To activate / deactivate automated navigation, which includes taking over the control from a pilot and manoeuvre through a predefined path (deliberative) along with an active collision avoidance mechanism (reactive). Before engaging an automated navigation, system shall perform a thorough 360-environment perception and check its capability for the expected functionality before confirming 'Ready'-ness to the user

Note that a “User” in the context of a UAV could be the remote pilot operating the UAV for a specific operational purpose such as delivery or surveying, or – in the case of passenger carrying UAVs - the users could be the passengers themselves.

Current EU regulations for UAV operations cover VLOS and BVLOS operations where the UAV is operated by a licensed remote pilot, and a number of limitations apply – for example, the UAVs may not carry passengers.

In the case of BVLOS operations, the remote pilot monitors that the UAV as is flying in accordance with its authorised flight plan, and intervenes with updates to the flight plan as needed, such as initiating a flight termination procedure which could include an emergency landing.

The BVLOS pilot does not generally directly fly the UAV through remote control of the UAV flight controls, but through updates to the flight plan instructions for the UAV to follow.

As UAV automation maturity develops together with the regulations and certification for UAVs, it may be possible that UAV flights can occur without any need for a remote pilot.

Operational design domain

From the standard definitions in the space of Automated Driving systems J3016 by SAE (Society of Automotive Engineers)[16], an ODD can be defined as “Operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics”.

In simple terms, ODD essentially defines the operating environment for which a system (or a maturity level of it) is designed for. Taking from there, the following set of categories, or characteristics define an ODD for a UAV:

- **Geography:** defines geographical limitations (per maturity level) in terms of flying vs no-flying zones, GNSS/5G signal reception, elevation, urban vs rural etc.
- **Environment:** Weather & atmospheric conditions, lighting conditions etc.
- **Scenery:** Static elements in the operating environment such as high-rise buildings, hanging cables, tall trees, erratic terrains etc.
- **Dynamic elements:** any moving objects in the operating environment

Dynamic pilot task and MRC

DPT or Dynamic Pilot Task defines who (human pilot or APS) in the current situation is responsible for performing pilot tasks such as vertical take-off & landing, navigation (deliberative & reactive), safe landing zone selection, and emergency landing etc.

Analogous to the prescribed DDT (Dynamic Driving Task) by SAE (in SAE-J3016), a DPT progression (with each level of maturity) for an UAV can be proposed as follows:

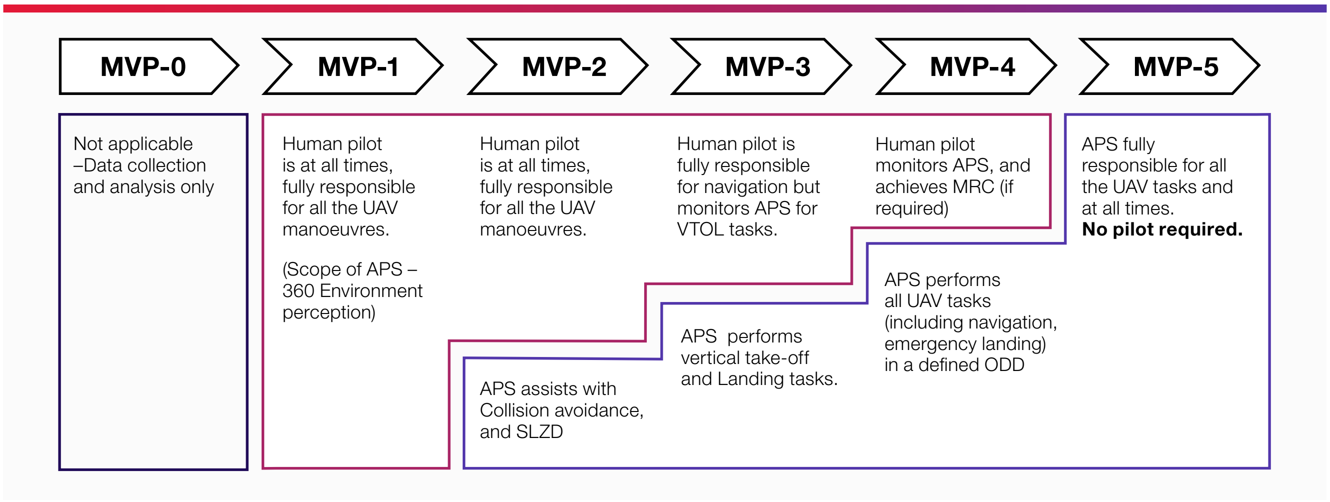


Figure 7: Auto-Pilot System logical architecture

As mentioned above, with the growing levels of maturity per each MVP, a fair distribution of tasks will be set between human pilot and APS. But there comes a situation where either the human pilot or the APS does not respond to a situation as expected, then the counterparts must step-in to control the vehicle and achieve an MRC (Minimal Risk Condition).

MRC can be defined as a tactical or operational manoeuvre triggered and executed by APS (auto-pilot system) or the human pilot to avoid any emerging hazard or even bring the vehicle (UAV) to a stable & risk-free state.

Note: Achieving an MRC using the APS is applicable only for MVPs 3 and above.

Development roadmap

Although the sensor integration will need to be a bespoke implementation for the drone use case, it is anticipated that the automotive sensors themselves can be reused in the aviation use case with minimal engineering effort to qualify them against the applicable standards for airborne software and electronic hardware. This is because each automotive sensor has been developed against a particular ASIL from ISO 26262 to meet necessary safety requirements against which validation activities have already confirmed that the sensor is achieving a sufficient an acceptable level of safety. A functional hazard assessment will still need to be performed for the sensors in the new use case, noting that the hazards for an airborne vehicle will be different to those for one on the ground. Nonetheless, the expectation is that the resulting safety requirements will share some commonality with those already implemented and qualified.

The following development timeline is proposed to achieve a required level of system maturity enabling successful operation of an Unmanned Aerial Vehicle.

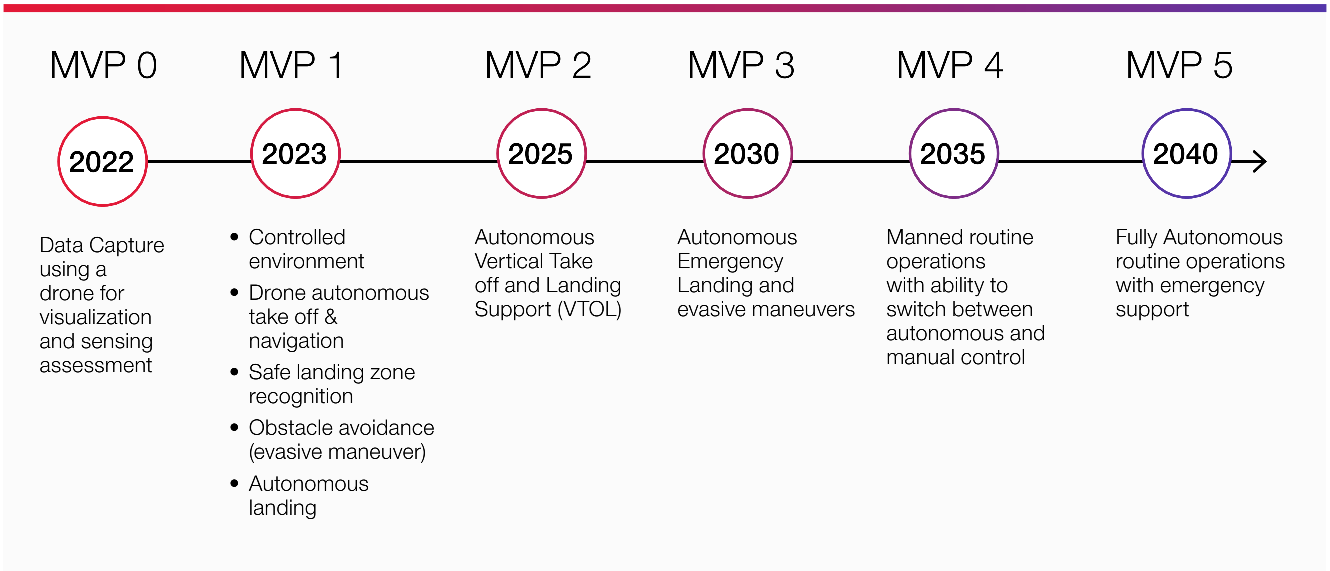


Figure 8: Development roadmap for autonomous landing and take-off

MVP0 initial data capture results

Initial data capture campaigns

In 2022 CGI IT UK and Continental Engineering Services have undertaken trials to establish the status of the technologies that will enable the Vision for Autonomous Landing and Take Off described in Page 17. These trials prove the concepts that lead to MVP0 as defined in the Urban Air Mobility Roadmap (see Page 21), and cover the architectural components of "Perception" and "Localisation" which will feed into the "Data Fusion" component as shown in Figure 6.

Perception component data capture

A UAV equipped with Continental's ARS540 premium, long-range 4D imaging radar equipment was flown in an open area in the south of England. This radar can detect an object's location in range, azimuth, elevation, and relative speed and is therefore likely to be a good representation of the equipment that will need to be fitted on AAM aircraft. The objectives were to verify the performance of the radar mapped terrain model against ground truth as derived from the cameras and on-ground observation.

Figure 9 illustrates the data that was obtained from the radar during the flight.

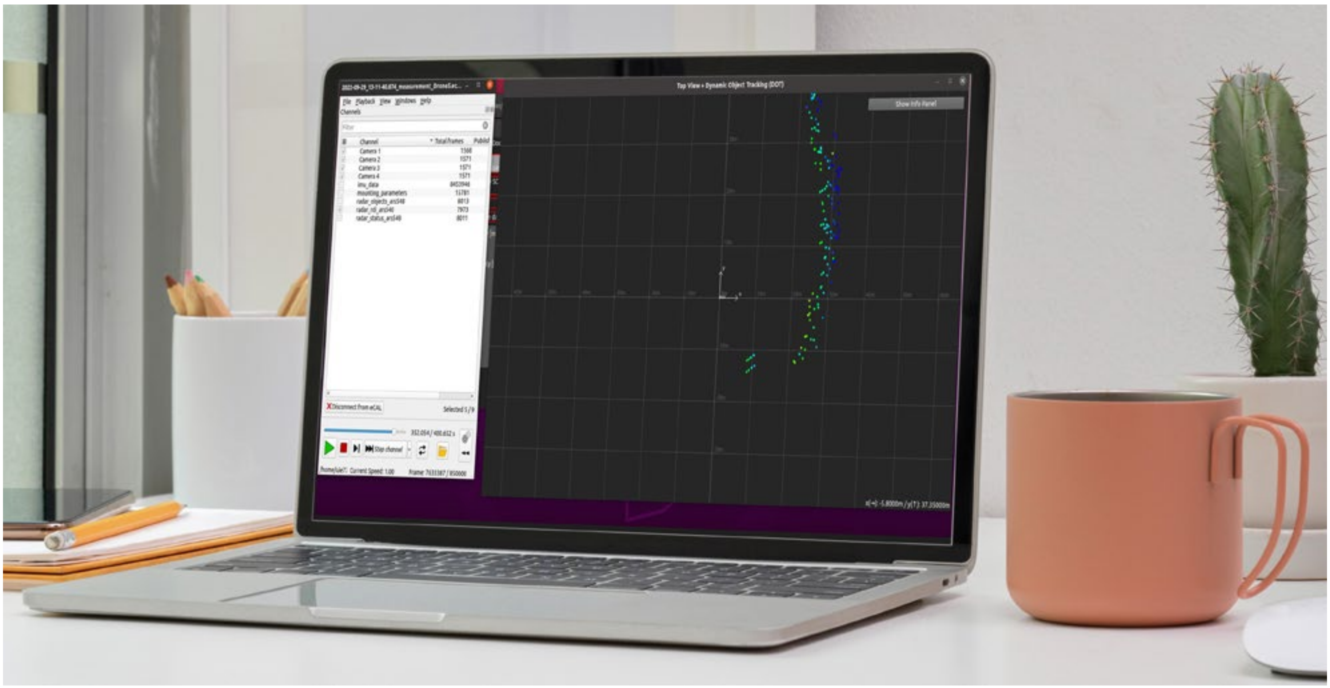


Figure 9: Radar detections from UAV survey

Figure 10 shows the same data mapped onto a plot of the trial area with an elevation scale (left), and aerial view of the same location (right) for reference. One interesting feature is the red (high elevation) mark in the centre of the data – this corresponds to a powerline which is not easily seen in the camera views.

This early survey has proven the principle of applying 4D imaging radar equipment to UAVs. There have been lessons learned in equipment mounting, electromagnetic compatibility, data acquisition and data calibration that can be applied in more extensive testing to complete the MVP0 stage of the roadmap.

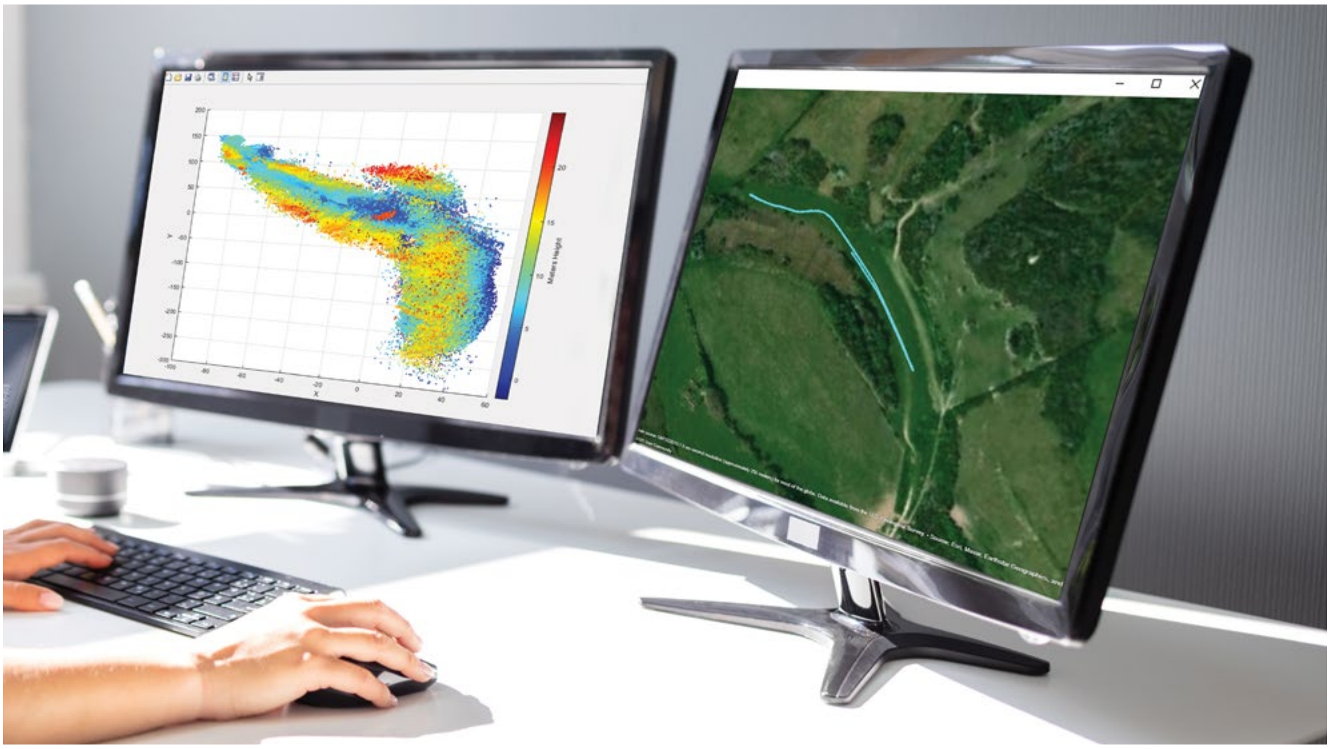


Figure 10: Transformed radar detections referenced to the UAV position

Localisation component data capture

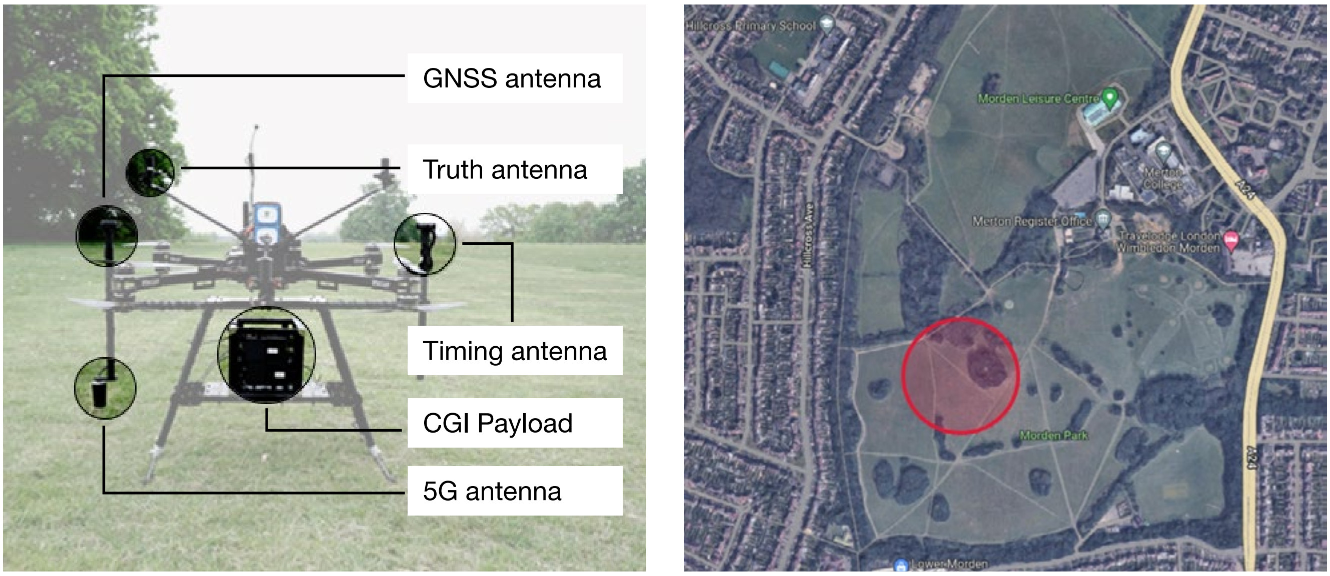


Figure 11: Flight trial equipment and location for combined GNSS and 5G navigation

The localisation of an AAM aircraft could be based on a combination of GNSS and 5G navigation to compensate for the limitations of GNSS both due to poor signal quality and to shielding in urban environments. Under an ESA supported project[3], algorithms were designed to determine the position of a drone with associated confidence levels for a combined GNSS/5G system and these were validated against both simulated and real-world data.

The real-world trials were based on flights of a UAV equipped with 5G and GNSS antennas and a self-contained bespoke GNSS and 5G data capture payload as shown in Figure 11.

The real world trials were used to explore the key areas for design and refinement of the system – for example the integration with an aerial platform and the characteristics of the 5G signals in different areas and at altitude.

Due to the current state of 5G roll out in the trials area and the limitations of the UAV test equipment, the algorithms were explored using simulated 5G signal data. These data were combined with real GNSS measurements in a factory test to model the performance of an operational system.

These results are illustrated in Figure 12 - it can be seen that position errors of up to 80m when using GNSS alone (in blue) can be improved to approximately 10m when 5G signals are also used in a hybrid positioning algorithm.

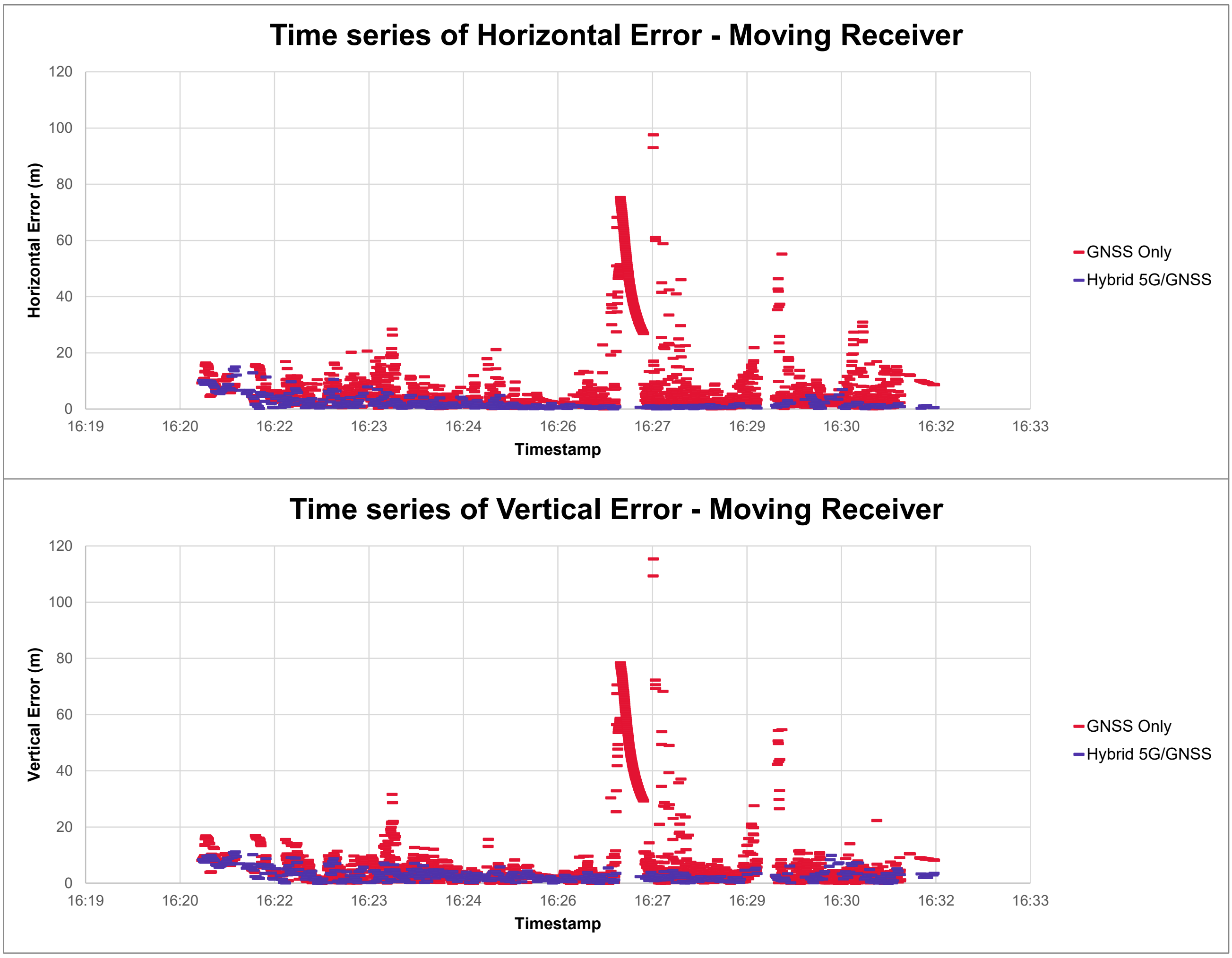


Figure 12: Factory Test Results: Navigation Error for Hybrid 5G/GNSS versus Galileo Only

In the AAM application, confidence in position is a very important consideration. The performance of the hybrid GNSS/5G positioning algorithms have been compared in representative scenarios when the GNSS signals are shielded by buildings. Figure 13 is an example of the result, expressed as horizontal position accuracy (in metres) in the y axis and dilution of precision in the x axis. The results show that whilst in the ideal GNSS clear sky view scenario (dark blue points) the criteria for certified performance are easily met, if the GNSS signals are greatly shielded in an "urban canyon" (grey points) there are some cases where the performance margins are not met, even with 5G signals contributing to the solution.

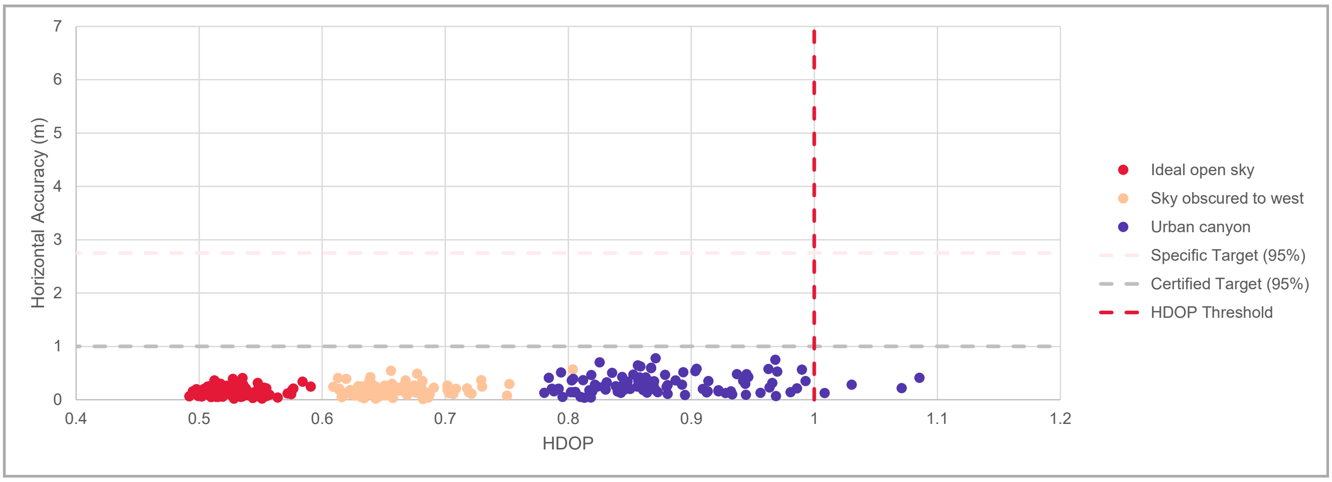


Figure 13: Hybrid 5G/GNSS horizontal positioning accuracy performance

The results on positioning performance have led to a recommendation for a review of the certified performance criteria for open flight of UAV in an urban environment. This review could take into account the contribution of the Perception component to the Comprehensive Environment Modelling that is required for AAM applications as shown in Page 19, recognising that sensors mounted on the AAM vehicle could compensate for the lower performance of navigation and localisation systems in the vicinity of urban take-off and landing sites.

Apart from this recommendation, the simulation and trials for hybrid 5G/GNSS navigation have identified the next steps in developing and refining the system, such as the requirements for accurate 5G base station position data, and suitable antenna beamforms for use above ground level.

Conclusion

A key enabler of the economic growth forecast for Advanced Air Mobility (AAM) is the ability to autonomously take off, navigate and land in complex urban environments.

The work carried out by CGI and CES, and presented herein, demonstrates that this is feasible and economically achievable. The visual and non-visual information required by an autonomous flight control system to become sufficiently aware of its own environment to derive actionable information for flight control inputs can be provided by sensors developed for autonomous driving. Data gathered during a series of ground tests and flight tests showed sufficient performance to suggest that an autonomous flight control system for safe operations in complex, urban environments can rely on a hybrid navigation solution that integrates automotive sensors with passive ranging in 5G networks and traditional GNSS receivers.

We used the experience gained as part of the flight trial programme to define a technology development roadmap to achieve the necessary levels of operational safety and security. The next step is to investigate the performance of the sensor suite in greater detail, and to build and test an integrated system that can detect and react to obstacles in a three dimensional space in real time.

We do, however, note that further regulatory development and standard setting is also required, if the full potential of AAM is to be achieved efficiently and economically.

We also note that the society which masters this key enabling technology first will gain a significant economic advantage in both supplying such hybrid navigation systems to AAM aircraft manufacturers, as well as gaining the benefits they enable.

We would like to thank the UK Space Agency (UKSA) and the European Space Agency (ESA) for their financial support of the 5G PNT trials.

For more information, please contact CGI.

Appendix A

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Appendix B

Glossary

Acronym / Term	Meaning
AAM	Advanced Air Mobility
ADS	ADS Group – UK Aerospace Trade Body
ADS-B	Automatic Dependent Surveillance – Broadcast
APS	Auto-Pilot System
ARP	Aerospace Recommended Practice
ASIL	Automotive Safety Integrity Level
ATOL	Automatic Take-Off and Landing
CA	Collision Avoidance
DAL	Development Assurance Level
DPT	Dynamic Pilot Task
EASA	European Aviation Safety Agency
EA	Environmental Monitoring
EUROCAE	The European Organisation for Civil Aviation Equipment
FOV	Field of View
Galileo	European GNSS service
GBAS	Ground Based Augmentation Services
GNSS	Global Navigation Satellite Services
GPS	Global Positioning System (US GNSS service)
ICAO	International Civil Aviation Authority
JARUS	Joint Authorities for Rulemaking on Unmanned Systems
LIDAR	Laser Imaging, Detection, And Ranging
MRC	Minimal Risk Condition
MVP	Minimum Viable Product
ODD	Operational Design Domain
OSNMA	Open Service Navigation Message Authentication
RPAS	Remotely Piloted Aircraft Systems
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SBAS	Satellite Based Augmentation Services
SFM	Structure From Motion
SLDZ	Safe Landing Zone Detection
TMPR	Tactical Mitigation Performance Requirements
UAV	Unmanned Aerial Vehicle

About CES

Since 2006, Continental Engineering Services (CES) has been active worldwide as an independently operating provider of comprehensive engineering services with currently more than 2,500 employees across 16 locations worldwide. CES has development teams throughout Europe, America, and Asia, including Frankfurt, Germany, Burgess Hill, UK and Litchfield, UK. With a mature camera and radar portfolio already in series production in automotive and off-highway applications, CES delivers functionality such as object detection, scene mapping and collision avoidance.

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