An Implementation Analysis of Communications, Navigation, and Surveillance (CNS) Technologies for Unmanned Air Systems (UAS)

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***Abstract*— The aviation industry and government agencies face a rapidly-emerging need for integrating large-scale populations of Unmanned Air Systems (UAS) into the worldwide controlled and uncontrolled airspace. Critical components for integration include the Communications, Navigation, and Surveillance (CNS) technologies necessary for ensuring safe UAS operations. Under NASA program NNA16BD84C, our work on CNS architectural concepts for the safe operation of UAS in controlled and uncontrolled airspace has introduced CNS architectures which must be analyzed in terms of implementation readiness.**

Controlled airspace operations for UAS are consistent with the needs for manned aviation in the worldwide Air Traffic Management (ATM) service. Uncontrolled airspace operations are consistent with the NASA Unmanned (air) Traffic Management (UTM) concept of operations. Implementation readiness is based on the NASA concept of Technology Readiness Levels (TRLs) ranging from TRL1 (basic principles observed and reported) to TRL9 (actual system flight proven through successful mission operations). In the architecture concepts, we have introduced a number of new CNS architectural elements which need to be correlated with TRL levels.

In this paper, we present our implementation analysis for communications networks, communications data links, navigation, and surveillance. Each area has been under active research and development during the course of the current NASA program which has produced studies on UAS CNS Requirements, UAS CNS Architecture for Controlled Airspace and UAS CNS Architecture for Uncontrolled Airspace. We have published our architecture concepts in major UAS-related conferences (including iCNS2017, IEEE Aerospace 2018, and iCNS2018) and will continue to seek additional publication opportunities. We look forward to continuing our work to realize a full integration testing scenario for both controlled and uncontrolled airspace operation.

Keywords—communications, networks, data links, navigation, surveillance, Unmanned Air Systems (UAS), Unmanned (Air) Traffic Management (UTM) service

I. Introduction

Under NASA program NNA16BD84C, our work on Communications, Navigation and Surveillance (CNS) architectural concepts for the safe operation of Unmanned Air Systems (UAS) in controlled and uncontrolled airspace introduced CNS architectures which must be analyzed in terms of implementation readiness. Controlled airspace operations for UAS are consistent with the needs for manned aviation in the worldwide Air Traffic Management (ATM) service. Uncontrolled airspace operations are consistent with the Unmanned (air) Traffic Management (UTM) concept of operations [1].

Implementation readiness is based on the NASA concept of Technology Readiness Levels (TRLs) [2] which ranges from TRL1 (Basic Principles Observed) to TRL6 (Demonstration in a Relevant Environment) to TRL9 (Actual system "flight proven"). In the architecture concepts, a number of new CNS architectural elements have been introduced which need to be correlated with TRL levels, as discussed in this document. We consider TRL6 as the lowest common denominator readiness level for all functional elements to realize fully integrated flight tests within the 1 to 5 year (2018-2022) timeframe. In the sections that follow, it can be seen that the TRL of most functional elements are already at TRL6 or above. Other functional elements are in advanced stages of research and development, and can be introduced into production tests as they mature. In summary, the core functional elements can be introduced into feasibility and practicality testing (both in lab settings and practical flight tests) in parallel with advanced research and development efforts.

In the following sections, we present our implementation analysis for communications networks, communications data links, navigation and surveillance. Each area has been under active research and development during the course of the current NASA program which has produced studies on UAS CNS Requirements [3], UAS CNS Architecture for Controlled Airspace [4] and UAS CNS Architecture for Uncontrolled Airspace [5].

II. UAS Communications Network Implementation Analysis

A. Introduction

Small Unmanned Air Systems (sUAS) (i.e., with vehicles less than 55lbs) have begun to enter the National Airspace (NAS) in increasing volumes with forecasts on the order of millions of units in the coming years. Due to the anticipated large-scale deployment, it would not be practical for small Unmanned Aircraft (sUA) operating in the uncontrolled airspace to be managed by the same pervasive Air Traffic Management (ATM) monitoring services necessary for manned aircraft and large UAS operating in controlled airspace (Classes A/B/C/D/E). Instead, sUAS operating in Class G uncontrolled airspace will require continuous CNS situational awareness (SA) as a network-based service called "Unmanned air Traffic Management (UTM)," while command and control (C2) messaging from UTM ATCs would be on a Manage-By-Exception (MBE) basis. In this context, MBE means that sUAS are required to operate in compliance with FAA Part 107 regulations [6], and only those sUAS deviating from regulations would be subject to preemptive and/or corrective UTM C2 directives.

Large UAS operating in controlled airspace will fall under the same Air Traffic Management (ATM) jurisdiction as for manned aviation worldwide, and will be subject to continuous C2/SA management by Air Traffic Control (ATC). The scale of the numbers of large UAS expected in the ATM will be many orders of magnitude less than for sUAS operating in the UTM, but the same communications network architecture elements apply. In particular, the communications network must support Internet-style communications where source and destination nodes can exchange Internet Protocol (IP) data units known as packets. The network can be either a standalone collection of private links, routers, switches, etc. or (more likely) an overlay configured over the global public Internet and protected by virtual private networks (VPNs)

In the following sections, we discuss the communications network functional elements in terms of technology readiness and any further R&D efforts needed to reach TRL6.

B. Internetwork – IPv6 (TRL9)

The global public Internet is the greatest data communications network success story in human history. It uses a data packetization protocol known as Internet Protocol version 4 (IPv4) which was originally deployed in test networks in the 1970s. Those early tests transitioned into what we now know as the worldwide Internet which interconnects billions of users with devices such as cell phones, tablets, laptop computers and even very small "Internet of Things" devices such as cameras, microphones, etc. However, the IPv4 addressing architecture allows for only 4 billion unique addresses such that great pains are taken to share the limited pool of addresses among nodes while still providing continuous service to all. The Internet is therefore now at a state where transition to a protocol with a greatly expanded address space is necessary, such that transition to a new protocol known as Internet Protocol version 6 (IPv6) is now underway.

IPv6 is now a full Internet standard and is implemented in nearly all public domain and commercial telephony, computing and network equipment products worldwide. The products are typically configured to accept either IPv4 or IPv6 networking service but prefer IPv6. Still other products such as low-end Internet of Things devices (e.g., home thermostats, surveillance systems, etc.) are IPv6-only. Major Internet Service Providers (ISP) such as Comcast are now also offering native IPv6 services to home users. As evidenced by these widely deployed and readily available products we categorize IPv6 at TRL9.

C. Autoconfiguration –DHCPv6 and IPv6ND (TRL5)

IPv6 includes adjunct services for automatically distributing IPv6 addresses and subnet prefixes to mobile devices such as UAS. A Stateless Address AutoConfiguration (SLAAC) service is offered by IPv6 Neighbor Discovery (IPv6ND) while a stateful IPv6 prefix delegation service is offered by the Dynamic Host Configuration Protocol for IPv6 (DHCPv6). UAS will require a mobile IPv6 subnet prefix that can travel with them wherever they happen to roam worldwide.

Both DHCPv6 and IPv6ND taken independently can be seen as TRL9 level functions. However, UAS data communications networks will require a combined DHCPv6/IPv6ND integration that works together to keep mobile prefix delegations active across access network address changes. The integration is categorized as TRL5.

D. Routing –The Border Gateway Protocol (BGP) (TRL9)

The Internet backbone consists of links (e.g., fiberoptics), bridges, switches and routers that are joined together in a global connected topology. Core Internet routers are responsible for determining the successive next hops for delivering data packets from a source Internet node to a destination. Each router therefore maintains a Routing Information Base (RIB) and Forwarding Information Base (FIB) for identifying the next hop and for forwarding packets to the next hop, respectively.

The Internet routing system is based on the Border Gateway Protocol (BGP) which has provided core routing services for many decades. BGP interconnects Autonomous Systems (ASes) in a mesh of peering arrangements between neighbor ASes. The set of all ASes worldwide makes up the global public Internet. UAS mobility event updates must be kept at the edges of the network and managed by a mobility service such as Asymmetric Extended Route Optimization (AERO). In this context, BGP is therefore classified as TRL9.

E. Security –OpenVPN (TRL9)

Since the ATM/UTM network services will be layered over the global public Internet, a Virtual Private Network (VPN) service will be necessary to protect the Confidentiality, Integrity and Availability (CIA) of the service. This includes both encryption and authentication so that ATM/UTM controllers can securely coordinate the operations of UAS via VPN tunnels across the Internet. These VPN tunnels must also support end system mobility so that secured sessions can remain active even as the UAS moves between network points of attachment.

A publicly available VPN client and server software distribution known as OpenVPN has been selected as the reference platform for secure UAS communications. Many commercial software vendors also offer VPN solutions, but these have the disadvantage of not providing open source code. OpenVPN technologies are stable and secure, and offer widely deployed services for Internet security. The TRL level indicated is TRL9.

F. Mobility – Asymmetric Extended Route Optimization (AERO) (TRL5)

Asymmetric Extended Route Optimization (AERO) is a network-layer mobility service that tracks UAS wherever they happen to roam across any of their available aviation data links. The service incorporates IPv6 as the network layer protocol, IPv6 ND and DHCPv6 as the autoconfiguration and mobility tracking service, BGP as the interdomain routing protocol and a mobile Virtual Private Network (VPN) service as the security layer. UAS that use AERO also configure a new type of IPv6 link-local address known as the "AERO Address" that links IPv6 routing with IPv6ND.

This model is instantiated in a public domain implementation of AERO based on the OpenVPN open source software distribution. The code runs on the linux and Android operating systems and supports all DHCPv6, IPv6ND and BGP operations. The AERO code itself is still undergoing advanced testing in network emulation and live network experiments, therefore its technology readiness can be classified as TRL5. The public domain KEA DHCPv6, OpenVPN and the Quagga BGP routing implementation are used. All of these implementations can be classified as TRL9.

G. Transport Layer (TRL9)

The transport layer is responsible for reliable and/or real-time segmentation of application data for presentation to the network layer, where the AERO mobile networking service conveys the data to the correct mobile or fixed end system. The Transmission Control Protocol (TCP) is a reliable end-to-end service that ensures that all data sent by the source is correctly received by the destination. For example, a UAS transferring a large file to an ATC could use TCP for its message segmentation, congestion control and flow control requirements. The ATC will acknowledge each byte that is received, and the UAS can retransmit any bytes that are lost. Since the UAS may be moving rapidly between network connection points, however, short C2 message directives with real-time delivery requirements such as prepared by Controller Pilot Data Link Communications (CPDLC) or Standards Agreement (STANAG) 4586 may be better served by the User Datagram Protocol (UDP).

Both TCP and UDP have been the foundational transport protocols in use in the Internet for many decades. They are robustly implemented in all major computing and network products, and are the most widely used transport facilities worldwide. Their TRL levels are classified as TRL9.

H. Applications (TRL5 – TRL9)

UAS applications include Command and Control (C2), Situation Awareness (SA), streaming media and general file transfer. CPDLC is a C2 messaging service for Air Traffic Management (ATM) directives between ATCs and remote pilots for UAS in operating in either controlled or uncontrolled airspace. This messaging service originated from and also applies to manned aviation applications for the Aeronautical Telecommunications Network (ATN) for both Open Systems Interconnect (ATN/OSI) and Internet Protocol Services (ATN/IPS). CPDLC is operational in ATN/OSI and hence is seen as TRL9 in that domain. It is currently undergoing advanced testing in the ATN/IPS domain in lab test environments, and can therefore be classified as TRL5 for ATN/IPS. Since the ATM/UTM service for UAS will be based on ATN/IPS, we therefore also see CPDLC as TRL5 for UAS operations. CPDLC messages will be carried by the UDP transport layer in that domain.

STANAG 4586 messaging is the standard C2 message set for remote pilots to control individual UAs within the UAS. The messages are carried by the UDP transport the same as for

CPDLC and are subject to loss and retransmission over the (best-effort) network layer service. Since AERO provides a best-effort mobile network layer service, STANAG 4586 messaging will receive the same best-effort services as for remote pilot to UAS communications in fixed networks and can therefore be considered as TRL9.

III. Implementation Analysis of Data Links for Unmanned Aircrafts

In this section, we present the implementation analysis of current and proposed data links for Aviation Traffic Management (ATM) and Unmanned Traffic Management (UTM).

A. Satellite Links (TRL8)

1. **Applicability**: Satellite links are used by almost all large UAs in controlled airspaces. Over the ocean, these are exclusively used for communication.

2. **Advantages:** Satellite constellations, today, cover most of the earth and so they are available in all parts of the earth.

3. **Disadvantages:** Two key problems with the satellite data links are: low data rate and large weight. The data rates per user are typically only a few kilobits per second able to support a few voice channels. The antenna sizes required at the receivers are too large for uses on a small UA. The total satellite data rate is also low so that only a few thousand aircrafts can be supported.

4. **Implementation Status:** Two satellites that are commonly used for aviation are Inmarsat Swift Broadband 5 and Iridium Next. Inmarsat Swift Broadband 5 provides 800 Mbps per Satellite. Iridium Next provides 72 Mbps/Satellite. We have set it at TRL of 8 (Subsystem development launch and operation).

B. AeroMACS (TRL5)

AeroMACS is the datalink designed by RTCA for ground communication at the airports.

1. **Applicability:** As indicated above, AeroMACS is designed for the airport ground segment. It can be used by both manned and unmanned aircrafts.

2. **Advantages**: It uses one of the latest communications technologies, and so it makes efficient use of spectrum.

3. **Disadvantages:** AeroMACS uses frequencies in 5.091-5.150 GHz (C-Band) that have been reserved for aviation. The spectrum band is protected and is, therefore, not a license-exempt band. Also it cannot be used off-airport by pilots trying to communicate directly with their UAs without an intermediary service provider.

4. **Implementation Status:** The standard is ready and has been demonstrated by several trials. We, therefore, set it at TRL of 5 (Technology Demonstration).

C. L-DACS (TRL5)

Foreseeing the need for aeronautical communication, EUROCONTROL developed two variants of aeronautical datalinks using the L-Band. L-DACS1 uses OFDM and is similar to WiMAX/LTE while L-DACS2 uses TDD and is similar to GSM. At this point, L-DACS1 is the leading candidate for adoption for data link for in-flight phase.

1. **Applicability:** L-DACS is designed for in-flight phase as a replacement for VHF Datalink 2 (VDL2).

2. **Advantages:** It uses 960 MHz to 1165 MHz in the L-Band. These frequencies are 5 times lower than those in C-Band used for AeroMACS. Therefore, these can reach much longer distance than C-Band technologies. It can be used by both the manned and unmanned aircrafts.

3. **Disadvantages:** L-DACS uses a protected band, which is excellent for a small number of aircrafts. Therefore, while L-DACS may be used by large UAs, another data link is required for small UAs.

4. **Implementation Status:** L-DACS is still being standardized. Since the technology demonstration is imminent, we set it at TRL of 5 (technology demonstration).

D. RTCA SC-228 UAS Data Link Activities (TRL5)

It is important to mention that RTCA special committee SC-228 working group WG-2 is chartered to develop minimum performance standards (MOPS) and minimum aviation system performance standards (MASPS) for command and control (C2). Phase 1 of SC-228 WG-2 focused on terrestrial control non-payload communication (CNPC) links for radio line of sight (RLOS) operation. The working group's white paper [7] describes their near-term plan. They plan to develop command and control data link MASPS by December 2018 and CNPC MOPS by June 2020.

E. WiFi (TRL9)

1. **Applicability:** WiFi and its variants are the most commonly used data links for small UAs. With some adjustments, a range of a few km can be reached. Its range is limited, but is acceptable for most photography and other applications.

2. **Advantages:** WiFi is the probably the most widely used wireless technology. Another advantage of WiFi is that it is implemented in all smartphones and, therefore, if a WiFi data link is used, smartphones can be used as controllers reducing the cost of the equipment.

3. **Disadvantages:** The key limitation of WiFi is its reach. The reach of a few km is not sufficient for most manned flights or most beyond the line of sight operations.

4. **Implementation Status:** As indicated earlier, WiFi is widely used. WiFi is at TRL 9 (Operational).

F. Long-Range WiFi (TRL3)

IEEE 802.11ah is a longer range version of WiFi. It uses the 900 MHz band (instead of 2.4 GHz and 5.8 GHz used by regular WiFi), and so it can reach several kilometers.

1. **Applicability:** This would be ideal for small UAs in near or beyond the line of sight operation.

2. **Advantages:** The band used is license-exempt, and so any sUA can be controlled by its pilot without an external service provider. At the same time, being similar to WiFi, it shares the advantage of low cost with WiFi.

3. **Disadvantages:** Since the spectrum is not protected, it can be used by anyone and, therefore, it is not suitable for controlled airspace and large UAs, where interference from other transmitters in the same frequency channel at the same time may not be desirable.

4. **Implementation Status:** The IEEE 802.11ah standard was completed at IEEE several years ago, but its adoption has been low, and there are very few implementations. The TRL is only 3 (need research to prove feasibility).

G. ZigBee (TRL9)

ZigBee, like the long-range WiFi, reaches longer distances than what is possible with standard WiFi.

1. **Applicability:** Like long-range WiFi, ZigBee also runs at 900 MHz band and therefore can reach longer distances than WiFi.

2. **Advantages:** It is also low cost and is, therefore, a protocol of choice for small UAs. In fact, most hobbyists, who build their own UAs use variants of Zigbee, called XBee and XBee Pro, 3DR, and RFD900.

3. **Disadvantages:** Most versions of ZigBee used in UA kits are proprietary versions named above.

4. **Implementation Status:** It is quite popular among hobby pilots. This technology is currently in use, and so the TRL is 9 (Operational) for small UAs.

H. Bluetooth (TRL9)

Bluetooth was developed for very short range communications. However, it has found its application in the small UA market.

1. **Applicability:** Bluetooth's range is limited to 30 m. This distance is sufficient for at least two applications: Follow me and swarm.

2. **Advantages:** Bluetooth is extremely low cost and small. It can be easily incorporated as a 2nd data link in addition to WiFi or ZigBee. It uses a license-exempt 2.4 GHz band.

3. **Disadvantages:** The main disadvantage of Bluetooth is that its range is too short and therefore it is used only as a secondary data link or indoor applications where shorter reach is not an issue.

4. **Implementation Status:** Bluetooth chips are widely available, and so it is widely implemented in all smartphones and several small UAs. The technology is operational and is in use and, therefore, has a TRL of 9 (operational).

I. Cellular and C-V2X (TRL9 / TRL5)

Cellular technologies such as 4G, LTE, and 5G are suitable for long-range communication.

1. **Applicability:** Cellular technology is globally available and, therefore, it competes with Satellite in many ways. It can be used by both small and large UAs.

2. Among the new features being introduced in 5G are "Cellular Vehicle to X" (C-V2X). Although this technology is being designed for automobiles, it can be easily adapted for UAs as indicated in our earlier reports.

3. **Advantages:** The biggest advantage of cellular is that the infrastructure exists in most habitats. This technology can be used for both small and large UAs.

4. **Disadvantages:** Cellular technology, although globally available, is implemented only mostly along the highways and only near populated areas. The cellular signal in remote areas is non-existent or weak.

5. **Implementation Status:** The cellular technology is widely deployed, and so it is at TRL 9. The upcoming C-V2X technology needs more trials and technology demonstration and is at TRL 5.

IV. UAS Navigation Implementation Analysis

Today's National Air Space (NAS) architecture dictates that Air Traffic Control (ATC) determines an aircraft's position based on Surveillance RADAR returns and from broadcast (e.g., ADS-B) information. The RADAR's precision degrades with increasing range from the RADAR site and due to non-line of sight signal returns (e.g., buildings, terrain) which contributes to a minimum separation between aircraft for safety. In a non-RADAR environment, aircraft must report their position as determined from GPS or navigation aids such as VOR and DME. This operational environment contributes to an even greater separation.

A key component of NextGen in 2025 is the transition from legacy navigation systems and RADAR surveillance to Alternate Precision Navigation and Timing (APNT) and Automatic Dependent Surveillance Broadcast (ADS-B) (Federal Aviation Administration 2012) for manned platforms operating in the controlled airspace [8].

The transition to ADS-B is dependent on precise aircraft reported position rather than surveillance or primary RADAR. GPS is currently the only navigation source approved for ADS-B with the accuracy required to meet performance objectives. Precise navigation and reduced separation in busy airspace (more aircraft flying efficiently through a smaller area) are the enablers. A secondary objective of dependent surveillance is a reduction in the required infrastructure and maintenance cost of the current NAS architecture. Combined, the plans to reduce separation minimums and eliminate existing infrastructure place a heavy burden on the GPS service. The safety of life concern and demand for high availability with few outages will require a backup to the vulnerable GPS to support UAS operating within the NAS and uncontrolled airspace.

NASA's concept for an UTM system would safely manage diverse UAS operations in the airspace above buildings and below crewed aircraft operations in suburban and urban areas. To support true position and timing, Boeing proposes the use of a multi-source navigation solution using a combined Global Navigation Satellite Systems (GNSS) with ground based Multilateration techniques (e.g., cellular, satellite, FM, WAAS, WiFi) with timing service protocol. To support relative positioning, Boeing proposes the use of unmanned-2-unmanned and unmanned-2-manned aerial systems Multilateration techniques combined with Automatic Dependent Surveillance Internet Protocol (ADS-IP).

In support of UTM, an affordable sUAS onboard architecture is needed to support Line of Sight (LOS) and BVLOS operations. The architecture should be defined in regards to sUAS compliance with minimum equipment list to support required communications, navigation, and surveillance plus detect and avoid (CNS + DAA) capabilities.

The onboard sUAS navigation architecture concept supporting Class "G" Airspace leverages multiple sources with a minimalistic addition of equipage with the consideration that "no one stand-alone technology" will augment GPS or provide greater position accuracy needed to operate with Class "G" Airspace. The proposed architecture is envisioned to host functions beyond navigation, such as, surveillance, communications, vehicle management, flight controls, maintenance, etc., with the use of the IMA computing architecture based on ARINC 653 real time operating system. The UAS navigation architecture concept is also envisioned supporting navigation functions by leveraging sensors for non-cooperative detect and avoid capabilities and signal characteristics from onboard communications systems. The following are recommended capabilities to support sUAS operating within Class "G" Airspace:

> Reliable Software and Hardware Architecture, Global Navigation Satellite Systems (GNSS), Multilateration RF Based Space/Ground Signals, ADS-IP & ADS-B, Image Based Navigation, IMU & On-board Clock, Ground-Based Navaids (GBN), Flight Management System, Detect and Avoid, and Aerospace communications

The key features supported by the recommended navigation architecture:

- Supports methods of augmenting GPS using different types of EO/IR imagery, signals of opportunities, modern augmentation systems, ensemble IMU/Clock, etc.
- Supports navigation error detection and correction with the ability to switch between different navigation source inputs.
- Supports dynamic navigation accuracy under various sensor, system, and component outage (e.g., faults, interference, spoofing, and IMU drift) over the course of typical flight phases.
- Supports the integration of a cost affordable certifiable software and reduced size, weight, and power hardware solution over.
- Supports integration of inference and algorithmic techniques to access geographic, spatial, and temporal information of both dynamic and static characteristics associated with the operational environment.
- Supports integration of planning, prediction, and chronicle recognition techniques to guide the sUAS and predict and act upon behaviors of vehicles.

To support the projection of large volume of sUAS operating within NAS, a multi-source navigation solution is desired to maintain increased coverage and to augment human in/on the loop operations with better than GPS-like position & velocity accuracy. The proposed navigation architectural solution will meet C-SWaP+P (cost, size, weight, & power +

performance) objectives through the use of integrated modular avionics and software virtual machine computing.

A. UAS NAV/ATM Technology Readiness

1) Global Navigation Satellite System (GNSS)

A GNSS is a satellite navigation system with global coverage. As of December 2016, only the United States' Global Positioning System (GPS), Russia's GLONASS and the European Union's Galileo are global operational GNSSs. The European Union's Galileo GNSS is scheduled to be fully operational by 2020. China is in the process of expanding its regional BeiDou Navigation Satellite System into the global BeiDou-2 GNSS by 2020. India, France and Japan are in the process of developing regional navigation and augmentation systems as well. – TRL9

2) Ground-Based Augmentation System (GBAS)

GBAS provides an internationally harmonized satellite-based alternative to the Instrument Landing System (ILS) for precision approach and landing. Extremely high accuracy, availability, and integrity necessary for Category I, and eventually Category II, and III precision approaches. GBAS is the only GNSS solution/alternative for Category III precision approach. – TRL7-9

3) RF-Based NavAid – Wide Area Augmentation System (WAAS)

WAAS, a regional space-based augmentation system (SBAS) operated by the Federal Aviation Administration (FAA), supports aircraft navigation across North America. WAAS provides service for all classes of aircraft in all phases of flight - including en route navigation, airport departures, and airport arrivals. This includes vertically-guided landing approaches in instrument meteorological conditions at all qualified locations throughout the NAS.

Although designed primarily for aviation users, WAAS is widely available in receivers used by other positioning, navigation, and timing communities. FAA is committed to providing WAAS service at the performance levels specified in the GPS WAAS Performance Standard. FAA is improving WAAS to take advantage of the future GPS safety-of-life signal to provide even better performance. The WAAS service is interoperable with other regional SBAS services, including those operated by Japan (MSAS), Europe (EGNOS), and India (GAGAN). – TRL9

4) Ground-Based Navigation (GBN) Aids

The mission of the Ground-Based Navaids is to ensure National Airspace System (NAS) Ground-Based Navigation solutions are implemented in the most efficient and effective manner to satisfy customer needs. It is expected that GBN will eventually be replaced with some variant of a GPS system in the future, WAAS & GBAS. – TRL9

5) IMU (Inertia Measurement Unit)

An inertial measurement unit (IMU) is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the magnetic field surrounding the body, using a combination of accelerometers and gyroscopes, sometimes also magnetometers. IMUs are typically used to maneuver aircraft, including unmanned aerial vehicles (UAVs), among many others, and spacecraft, including satellites and landers. – TRL9

6) Onboard Clock

A real-time clock (RTC) is a computer clock (most often in the form of an integrated circuit) that keeps track of the current time. Most RTCs use a crystal oscillator, but some use the power line frequency. In many cases, the oscillator's frequency is 32.768 kHz. This is the same frequency used in quartz clocks and watches, and for the same reasons, namely that the frequency is exactly 2^{15} cycles per second, is a convenient rate to use with simple binary counter circuits. Many commercial RTC ICs are accurate to less than 5 parts per million. In practical terms, this is good enough to perform celestial navigation, the classic task of a chronometer. In 2011, Chip-scale atomic clocks were invented. Although more expensive, they keep time within 100 nanoseconds. – TRL9

7) Air Data Computer

An air data computer (ADC) is an essential avionics component found in modern glass cockpits. This computer, rather than individual instruments, can determine the calibrated airspeed, Mach number, altitude, and altitude trend data from an aircraft's pitot-static system. – TRL9

B. UAS NAV/UTM Technology Readiness

1) Low Earth Orbital (LEO) Space Vehicle (SV) Constellation

A signal of opportunity source of navigation and timing is with the use of a candidate communications source which operates within the low earth orbital constellation called Iridium made up of 66 satellites. There has been a number of research efforts conducted proving low earth orbital signals provide greater coverage and even improved navigation accuracy over traditional GPS signals due to the signal strength being approximately 300 to 2400 times stronger than GPS. Iridium also has the ability to provide positioning information using only one satellite vehicle source due to the rapid movement of each satellite. Additionally, the Iridium signals support deep indoors navigation and timing which is very useful for sUAS operating in dense urban areas. – TRL4-6

2) Signals of OPportunity (SOP) – Cellular

Another method of navigation is the use of cell phone towers and transmissions to create beacons serving as pseudo-lites for UAS's. – TRL4-6

3) Precision Image Registration (PIR) Terrain Aided Navigation

For sUAS operating within a suburban and urban areas, there is a high probability for imagery to be used real time for maintaining position references. A suitability analysis for a given area of operation can be performed to assess the likelihood of having enough features extraction points available to support real time image-based navigation & guidance (i.e. true position, velocity, and attitude) using Digital Terrain Elevation Database (DTED). With this approach, time referencing can be provided by approved communication protocol(s). Additional, the spatial temporal image model(s) used for position calculation can be used to optimize DAA capabilities.

To maintain GPS-like precision over long distances absolute position update techniques are necessary. Two promising "Vision-Based Navigation" technologies are terrain correlation and scene correlation to support UAS navigation when no other navigation aids are available.

Another technical approach of image based navigation is by using a technique called Precision Image Registration (PIR) to correlate pixels from a real-time image in regards to a geo-spatial image database (e.g., DTED). – TRL 7-9

4) *Ensemble Averaging IMU/Clock Approach*

To handle periods of time without GPS or GPS-like source information, Boeing purposes the use of an ensemble average technique using multiple IMUs and clocks. The ensemble averaging is the process of creating multiple models and combining them to produce a desired output, as opposed to creating just one model. Boeing's approach should provide a low cost multiple 10-axis IMU & Clock machine learning solution with ease of integration on any size manned or unmanned aircraft. TRL 2-3

V. SURVEILLANCE

A. *Introduction*

In terms of surveillance the current project started with the definition of UAS surveillance needs to enable operations within both controlled and uncontrolled airspaces. In order to satisfy those needs, a series of surveillance requirements was established. Then, based on those requirements, we defined and designed architectures of different cooperative and non-cooperative surveillance systems for the two different environments already mentioned: controlled and uncontrolled airspaces.

B. *Technology readiness analysis*

1) *Approach to the surveillance proposal*

A series of general assumptions were established at the beginning of the project in order to provide the basis of a coherent development roadmap:

- The final objective of the surveillance developments would be to keep and potentially improve current aeronautical safety and security criteria for the proposed architectures.

- Two clearly differentiated scenarios were specified: An aeronautical traditionally conservative scenario for controlled airspaces, and a revolutionary and futuristic scenario to fulfill the requirements of uncontrolled airspaces.

- Developed system would minimize the impact on ATC procedures and modes of operation.

- Emerging technologies available in the short-medium term should be explored in order to provide novel, functional, safe and secure surveillance solutions.

As all the surveillance architectures proposed during the project share the same principles, they all have some common features. Some of these can be considered more conservative than others. Among the common conservative features of the architectures proposed are the following ones:

- They make use of communication technology currently ready: Cellular, Satellite, Wi-Fi, C-V2X, DSRC…

- They make use of positioning technology currently ready: GNSS, inertial systems…

- Especially in the case of controlled airspaces, the integration with current systems has been taken into account. In this scenario, it has been considered that the proposed solutions should always be transparent for the ATC.

On the other hand, there are also some common innovative points shared by the architectures proposed:

- They have been designed to foster upcoming UAS regulations.

- They focus on the development of different pieces of a complete automated surveillance management system working under the principle of managed by exception.

- Security has been a priority. All architectures proposed follow the security-by-default design principle.

- We have focused on the proposals of architectures with highly-available while affordable.

- Extensive use of IT/Cloud architectures in order to provide scalability.

2) Technology readiness level for the surveillance architecture proposals

During the project several surveillance systems have been proposed. The systems depend on supporting technologies, including:

- GNSS (TRL9)
- V2X Communications (covered under data links)
- Comms/surveillance onboard computer (TRL9)
- Cloud Computing (TRL9)
- PKI (TRL9)
- Low power – high frequency radar (TRL6)
- HD/IR cameras (TRL8)
- Lightweight multi-core image processing (TRL6)
- Multilateration/signature analysis (TRL6)
- Multipoint acoustic sensors (TRL7)
- High-efficiency LEDs, Acoustic Transducers (TRL8)

The readiness level of the surveillance architectures proposed does not only depend on the TRL of their supporting technology. In order to express how deep we have defined the systems, we have sorted them by "Technology Definition Level (TDL)". TDL is not a standard scale; it is a term we have coined with the only purpose of providing the reader with an idea of the "remaining work" needed to be able to implement the following surveillance architectures proposed so far:

- **ADS-IP:** ADS-IP is a centralized, automated and cooperative surveillance system. It stands for Automated Dependent Surveillance over IP. The main functionality of ADS-IP is to provide a system able to manage the surveillance data of UAs flying within a specific area. While current surveillance systems rely on the use of RF-based channels ADS-IP makes use of an underlying IP-based communications network. The use of IP networks and communication protocols enable ADS-IP to overcome most of the limitations and vulnerabilities of current surveillance systems (such as ADS-B or SSR). It uses IP transmission channels to manage the data interchange between UAs and a server on ground, and between such server and other actors such as an automatic traffic supervisor or the fleet owner. A server on ground acts as the core of the system, gathering all the navigation data transmitted by the UAs and distributing it accordingly to the needs of each actor. – TDL8

- **uADS-IP:** Conceptually, µADS-IP functionalities are very similar to traditional ADS-B but adapted to the operation mode expected by sUAS in class G airspace. µADS-IP is an automatic dependent surveillance system proposal. As a dependent system, it is the own UAS the one which determines its position (by GNSS or any other means) and broadcasts it so that other vehicles or systems on the ground can receive it and make a picture of the traffic within a determined airspace.

  First, its transmission power is lower than ADS-B's, which combined with other transmission coding techniques enables a much higher density of transmitters and receivers for a determined operation area. DSRC and C-V2X are candidate carriers to support the transmissions. With respect to the security dimension, an encryption layer is proposed. The proposal is based on a symmetric encryption for the broadcasted surveillance data through RF channels. The use of a PKI is proposed to distribute the encryption key for the µADS-IP messages through secure communication channels (Internet-based) when these are available. – TDL4

- **Drone Surveillance Radar (DSR):** Primary Surveillance Radars (PSR) have traditionally represented the main non-cooperative surveillance system for controlled airspaces. Current PSRs, however, cannot be considered for sUAS over Class G airspaces. Their low accuracy as well as their lack of ability to uniquely identify targets and to detect small targets, make them unsuitable for the purpose of integrating sUAS operations within uncontrolled airspaces. However, the technology can be adapted by using different frequency transmission bands to be able to detect small targets.

  The market is already offering PSR-based solutions, usually called Drone Surveillance Radar. They are oriented to the protection of determined specific areas (e.g., critical infrastructures, national borders or military bases). These kind of solutions are based on the deployment of high-performance radar sensors. – TDL9

- **Image recognition for positioning and identification - optronics:** The word "optronics" is a combination of optical and electronics. It involves detection, image processing and stabilization functions. Solutions of this kind make use of long-range HD infrared cameras which allow to target, identify, and provide visual data from the sUAS. – TDL7

- **Electromagnetic/acoustic signatures analysis for positioning and identification:** These solutions consist of passively eavesdrop on the RF communication between the sUA and its controller. By using this technique, it is possible to identify the frequency of transmission, the MAC address of the UA, or the frequency of packet communication. Other approaches try to identify the electromagnetic fields and noise created by the spinning of the propellers and the sUA vibration. – TDL7

- **Light/acoustic signaling for safety enhancement:** light and acoustic signaling could be considered as cooperative surveillance methods. These kinds of methods present a very short range, slightly higher in the case of light signaling. They are not able to transmit any data to the ground, they are just beacons to let know the controller their presence.

  Light signaling could be improved by using a simple modulation pattern to encode and broadcast some limited parameters (e.g., the unique aircraft ID). The same principles of this basic communication could also be applied to establish a ground-to-air communication channel to transmit very specific orders by a police officer or other agent authority in case of emergency (such as abort sUAS flight). – TDL5

The results of the analysis show that the technology needed to implement our proposed architectures is already available, which is a big benefit when thinking on systems to be deployed within the next 3 to 5 years.

VI. Summary and Next Steps

In this document, we provide an implementation analysis of the Communications, Navigation and Surveillance (CNS) technologies available both today and within the 3-5 year timeframe. We discuss the Technology Readiness Levels (TRL) of the various technologies at the current time of this writing. From this analysis, we show that the majority of the technologies that have been proposed in our architectures are currently ready for integrated flight testing, with advanced technologies already under experimentation in lab settings and will be ready for flight testing in the 2020-2022 timeframe.

This implementation analysis follows our architecture concepts for controlled and uncontrolled air space published in earlier program work items and also aligns with a number of published and pending publications at major UAS CNS conferences. The work is consistent with the worldwide Air Traffic Management service and provides a path for a unified airspace for both manned and unmanned aviation.

In terms of next steps, our team is ready to join the effort of integrating our technologies into actual flight tests so that the concepts can be proven. At the same time, we observe that continued research and development in the lab environment is necessary in the near- to mid-term so that advanced features can be rolled into the ongoing qualification and certification efforts. Our team is prepared to coordinate those efforts with the rest of the unmanned aviation community.

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