DEVELOPING A PNT ARCHITECTURE FRAMEWORK

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ABSTRACT

Positioning, Navigation and Timing (PNT) data is integral to the safety, security, and prosperity of nations. However, in most cases the role of PNT services at the Enterprise or even Government/National is not clearly understood, and the degree to which a nation is dependent on PNT services often remains undefined. This paper presents a framework for understanding and managing for the long term, a complex strategic PNT environment including how policy, strategy, threats and organisation infrastructure fit together with a hybrid technology mix, to contribute to the delivery of PNT services so users can improve their resilience.

1. INTRODUCTION

Position, Navigation and Timing (PNT) is a collective term used to describe the provision of data necessary to calculate position and/or velocity and/or time in a given reference frame, in four dimensions, i.e. 3D position and a common time reference, to a degree of accuracy and integrity sufficient to service diverse user needs.

The source of this PNT data can be aids-to-navigation, measurements of relative or absolute velocity or simply a specific point in time when a particular event occurred. This data has traditionally been generated and broadcast in a variety of ways ranging from highly precise timing sources such as atomic clocks that are calibrated and synchronised to an international common time reference (e.g Coordinated Universal Time (UTC)) for a local user; a network of masts in specific locations transmitting timing and location identification signals and data to enable regional users to calculate their position; and over the past 25 years the deployment of satellite constellations such as the US Global Positioning System (GPS), which can deliver both high precision 3D position and highly stable and precise time and frequency traceable to the UTC global standard.

PNT data is now integral to the safety, security, and prosperity of nations. However, in most cases the role of PNT services the Enterprise or even Government/national level is not clearly understood, and the degree to which a nation is dependent on PNT services often remains undefined. This is noted well in in the UK Governments' Satellite-derived time and position: Blackett review (Government Office for Science, 2018) which notes that PNT[1] information is used by every Critical National Infrastructure (CNI) sector. It enables vital operational aspects of transportation, all aspects of communications, energy production and distribution, finance and banking, healthcare, and emergency response operations.

PNT is also critical to the UK's national security supporting command, control, and communications capabilities, and to the cyber enterprise. The loss of PNT services from modalities such as Global Navigation Satellite Systems (GNSS) (like GPS) will have a significant impact on our economic wellbeing (London Economics, 2017)

[1] For clarity, PNT also includes attitude/orientation information where the use case requires it.

Over the last 10-15 years, many studies, papers and research across Governments, academia and the private sector have analysed PNT and its implementation in CNI, a broad summary can be made when applied, as an example, to the UK:

- The UK is critically dependent on PNT information – principally accessed through GNSS, specifically GPS. There is no UK PNT Strategy to identify, mitigate, manage and/or monitor the UK's dependencies.
- There is a clear need for a coordinated approach to achieving the provision of PNT services to enable a resilience improvement and where needed, assurance of services to support CNI and the wider economy, Dedicated specialist resources are likely to be deployed to develop the strategy and oversee its implementation.
- Solutions to the UK's PNT requirements must be diverse, incorporating a holistic mix of technologies (terrestrial and space-based) as no single technology is likely to deliver sufficient resilience for critical users of PNT information.
- There remains a low level of understanding about the dependencies on, and risks to, PNT in many UK sectors. There remains a risk that users are not aware of the vulnerabilities they have to disruption – especially users of GNSS-provided time and frequency services.
- Resilient services need to be available across borders so the UK should work with partners on common PNT interoperable infrastructure for both space and terrestrially based assets. A focus must be on the risk profile of PNT, to establish the level of threat to PNT services as well as the primary and second order impacts across a range of sectors in the event of a loss of PNT.
- There exists an opportunity to fully review and where necessary amend, Legislation, Regulation and Standards (LRS) across the PNT domain. Correct development and implementation of standards are a driver for innovation and should be part of the overall PNT resilience improvement solution.
- The skills pipeline to sustain PNT competencies for the medium and longer-term is an area of concern and needs to be significantly improved in the UK.

This paper is focused on developing a framework which could be used for the coordination of PNT in the UK or a large enterprise. It proposes an architecture and approach that addresses the complexity of multiple technologies coming together in a coherent way, integrates existing developments and programmes, and includes the elements of policy and strategy that are necessary in any Government or enterprise.

This paper is based upon authors experience working within the UK Government developing the evidence base for a UK PNT Strategy. It does not represent UK Government policy nor indicate any direction that the UK Government may take to resolving PNT resilience challenges.

2. COORDINATION FRAMEWORK

PNT is a complex landscape with solutions that span technology, information, facilities, process, and human activity systems. The technology aspects for PNT will likely encompass space, quantum, radio frequency (RF), software, cloud computing, mapping, data analytics and other systems and components. The interactions between multiple systems are complex and need to be coordinated and managed efficiently to achieve the objectives of access to resilient and assured PNT services.

To understand and structure this complex environment and put it into a context that Government(s) and enterprises can readily understand and manage, it is necessary to determine a framework and approach that is communicable and within which the multiple areas of policy, strategy, economics, and technology can align.

PNT is particularly suited to this approach because:

- Coordinating PNT services as a complex landscape of components interacting as a "System-of-Systems (SoS)" requires a structured and coherent approach.
- It introduces common terms of reference and metrics, denotes a place for everything and how it relates to everything else.
- It reduces fragmentation, and risk of un- or under-addressed aspects of PNT and associated risks, issues, and opportunities.
- It promotes a strategic approach to address an overall enterprise or national PNT capability for all critical and non-critical infrastructure users.
- It enables service providers and programmes to operate independently yet ensure that they support the overall PNT mission and goals.
- It enables overall coordination and reduces duplication (lowers overall cost)

A framework (Figure 1.) shows these aspects graphically and introduces the hierarchy approach to PNT. The purpose therefore of this PNT Architecture Framework is to provide a method to coordinate the strategic and implementation aspects of this concept, including the SoS approach, across PNT service supply, through derivation then use of PNT information itself.

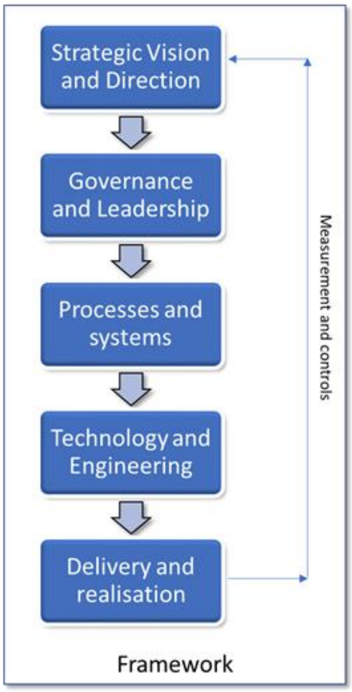

Figure 1: A typical structured framework

3. ARCHITECTURE FRAMEWORK AND SYSTEM-OF-SYSTEMS METHODOLOGIES

Enterprises and international businesses and some Government departments such as the UK Ministry of Defence (MoD) have been studying complex systems for some time, and several frameworks already exist that can effectively be employed to bring much needed structure and rigour to this PNT challenge. The MoD Architecture Framework (MODAF)(Ministry of Defence, 2020) is an internationally recognised enterprise architecture framework developed by the MoD to support defence planning and change management activities. The US Government have published similar approaches. (US Government 2012)

The Open Group Architecture Framework (TOGAF) (The Open Group) standard is a proven Enterprise Architecture methodology and framework used by the world's leading organizations to improve business efficiency.

For the complex PNT problem within the context of a structured framework, TOGAF is proposed as a basis to build a relevant framework for PNT, as it is best suited for use in conjunction with other frameworks that are more focused on specific deliverables for vertical sectors. From a cross-Government or enterprise perspective, TOGAF is also well suited to work with multiple departments, all of whom may have their own processes, programmes, and methodologies.

The objective is the creation and implementation of a specifically developed, yet flexible, architecture framework that addresses an overall national or enterprise PNT capability, encompassing strategy, policy, requirements, threats and hazards, and all critical and non-critical infrastructure users, whilst still enabling delivery programmes [existing or candidate] to operate and deliver independently and ensure that they support the overall PNT mission and goals.

TOGAF also embraces the ISO/IEEE terminology and approach when defining an enterprise architecture. *"The structure of components, their inter-relationships, and the principles and guidelines governing their design and evolution over time."* (The Open Group)

3.1 TYPES OF SYSTEM OF SYSTEM (SOS)

ISO/IEC/IEEE 21839 (IEEE) provides a definition of SoS and constituent systems within it:

- System of Systems — A set of systems or system elements that interact to provide a unique capability that none of the constituent systems can accomplish on its own.
- Constituent Systems — Constituent systems can be part of one or more SoS, each constituent being a system by itself, having its own development, management goals and resources, but interacts within the SoS to provide the unique capability of the SoS.

ISO/IEC/IEEE 15288 Annex G (IEEE) also describes the impact of these characteristics on the implementation of systems engineering processes. Because of the independence of the constituent systems, these processes are in most cases implemented in both the constituent system and the SoS but need to be tailored to support its specific characteristics, which may be necessarily different from its constituent parts. These process differences can apply to the organisation, the management and governance, the technical implementation and processes contained within and the verification and validation of constituents versus SoS. This is the purpose of the architecture framework.

SoS occur in a broad range of situations and where the "SoS is treated as a system in its right", an SoS can be described as one of four types (Maier (1998), Dahmann and Baldwin (2008)):

Type	Description
Directed	The SoS is created and managed to fulfil specific purposes and the constituent systems are subordinated to the SoS. The component systems maintain an ability to operate independently; however, their normal operational mode is subordinated to the central managed purpose;
Acknowledged	The SoS has recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on cooperative agreements between the SoS and the system
Collaborative	The component systems interact more or less voluntarily to fulfil agreed upon central purposes. The central players collectively decide how to provide or deny service, thereby providing some means of enforcing and maintaining standards;
Virtual	The SoS lacks a central management authority and a centrally agreed upon purpose for the SoS. Large-scale behaviour emerges—and may be desirable—but this type of SoS must rely on relatively invisible mechanisms to maintain it.

Table 1: Types of System of System, based on Maier (1998), Dahmann and Baldwin (2008)

3.2 SEVEN PAIN POINTS OF A SYSTEM-OF-SYSTEM

INCOSE in its System Engineering handbook (INCOSE, 2015) set out the typical challenges and conflict area between the SoS activities and the constituents. These are summarised and recounted below as "seven pain points" and must be addressed in any SoS development, especially in an Enterprise or Governmental setting.

- SoS Authority and Governance. In a SoS each constituent system has its own 'owner', stakeholders, users, processes, and business model. There is a heavy reliance on an agreed common purpose and motivation for constituents to work together towards collective objectives which may or may not coincide with those of the constituent systems.
- Leadership. The lack of common authorities and funding pose challenges for SoS especially for leadership, coherence, and direction in a multi-organisational environment.
- Constituent systems' perspectives. SoS are typically comprised, at least in part, of in-service systems, which were often developed for other purposes and are now being leveraged to meet a new or different application with new objectives. This is the basis for a major issue facing SoSs; that is, how to technically address issues which arise from the fact that the systems identified for the SoS may be limited in the degree to which they can support the SoS.
- Capabilities and Requirements. Ideally engineering processes begins with a clear, complete set of user requirements and provides a disciplined approach to develop a system to meet these requirements. Typically, SoS are comprised of multiple systems with their own requirements, working towards broader capability objectives. Ideally the SoS capability needs are met by the constituent systems as they meet their own requirements, but in many cases the SoS needs may not be consistent with the

requirements for the constituent systems. In these cases, the SoS needs to identify alternative approaches through changes to the constituent systems or additions of other systems to the SoS. This is a significant challenge for PNT systems due to the diverse nature of the use cases where PNT is essential.

- Autonomy, Interdependencies and Emergence. An independent constituent system may change independently of the SoS, along with interdependencies between that constituent system and other constituent systems which adds to the, and introduces complexity or unknown elements in, the SoS. Specifically, this can lead to unanticipated effects at the SoS level leading to unexpected or unpredictable SoS behaviour.
- Testing, Validation, and Learning. The fact that SoS are typically composed of constituent systems which are independent of the SoS poses challenges in conducting end-to-end SoS testing as is typically done with systems.
- SoS Principles. SoS is a relatively new area, with the result that there has been limited attention given to ways to extend systems thinking to the issues particular to SoS. Work is needed to identify and articulate the cross-cutting principles that apply to SoS in general, and to developing working examples of the application of these principles. There is a major learning curve moving to a SoS environment, and a problem with SoS knowledge transfer within or across organizations

4. A PNT ARCHITECTURE FRAMEWORK

Taking these best practice methodologies into account, a PNT architecture framework will enable appropriate decisions about capability or R&D investment to be made at the right time, in the right context, by the right people.

The proposed framework design consists of five specific functions (Figure 2):

- Strategic Architecture - Strategy, Vision, Principles, Mission and Objectives.
- Business Architecture - How PNT will be coordinated cross government/enterprise and the intelligent customer.
- Services Architecture - Service Development, to meet users' needs from PNT.
- Technology Architecture - The PNT technology mix to provide a portfolio of capabilities for the necessary resilient PNT services.
- Service Realisation - The delivery of SoS-based PNT capabilities.

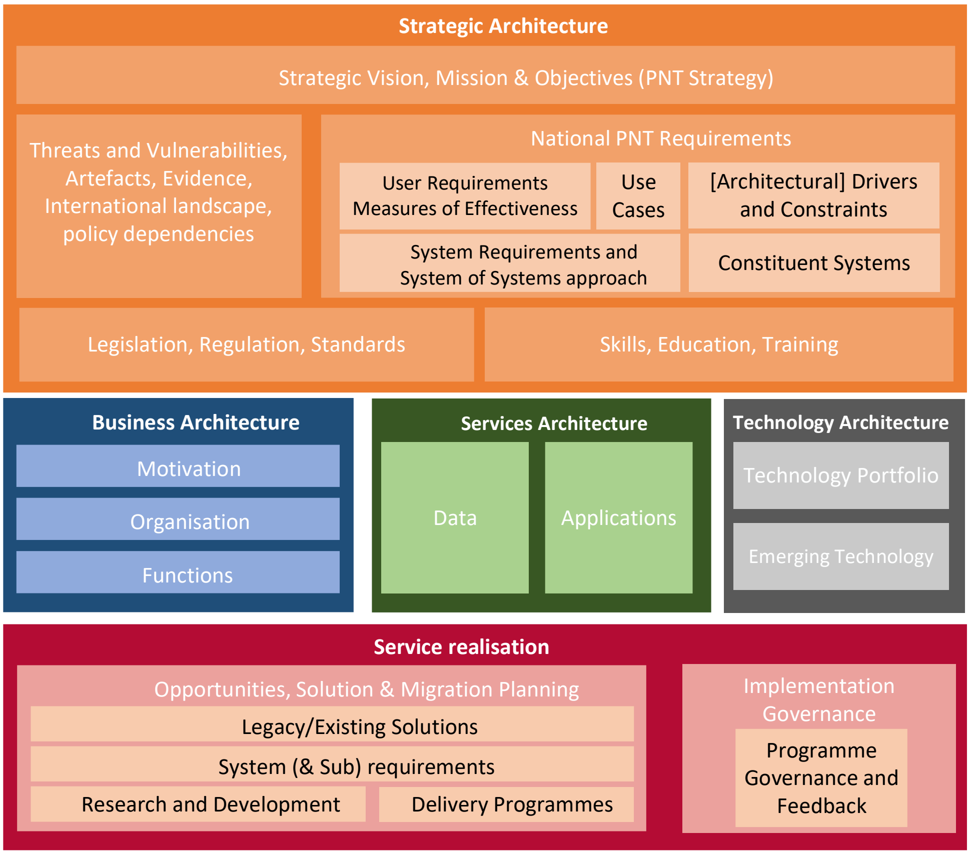

Figure 2: PNT Architecture Framework

Within this PNT architecture framework the sum of the multiple diverse and discrete parts, will deliver the necessary resilient and assured PNT services to users, meet their requirements and ensure that organisational and (where appropriate), national interests are protected from PNT disruption, and vulnerabilities mitigated. Individual PNT capabilities within the system-of-systems will contribute to the whole while not necessarily having to address the full spectrum of requirements on its own.

Each section of the Architecture Framework will now be described in detail[2].

4.1 STRATEGIC ARCHITECTURE

The strategic architecture provides the necessary direction and guidance to the architecture framework. The vision communicates the "why" and supports the "common goal(s)" (sometimes called "what good looks like"), for all - regardless of their community of interest or specific PNT role.

Many nations, including the UK, have recognised the need to enhance the resilience of PNT services (UK Government, 2021), and these policy directives must be included in any framework to provide the direction and overarching policy driver. This policy driver must be translated into a vision and a set of principles under which any strategic decisions, frameworks or delivery capability decisions are made. If the vision and principles are met then PNT users

[2] For requirements (out of scope of this paper) User Requirements (UR's) for the system-of-systems (i.e. user requirements for PNT in the round) must be translated into System Requirements (SR's) to enable providers to understand how their technology can contribute to the 'whole'. This is a non-trivial task and if carried out incorrectly will lead to cost overruns and not delivering the resilient PNT that users require.

will have the means to access sufficient services to derive or provide PNT such that PNT data is not interrupted, remains trustworthy, and ensures that the users' own activities and/or services will not be interrupted regardless of any discontinuity in the provision of any contributing PNT services.

For the purposes of this paper, a vision and set of principles have been hypothesised to represent a potential national policy response and is shown in Figure 3.

Figure 3: Hypothesised PNT Vision and Principles

The vision for the strategic framework used here is to "Ensure that this enterprise has comprehensive, collaborative, interoperable, seamless, and sustainable access to assured and resilient PNT services to protect people, enhance prosperity and support global influence"[3].

A set of representative principles can be created to address delivery of this vision:

1. The critical need to reduce dependency on vulnerable systems, over-dependence on single solutions and to deliver diversity, duality, and redundancy commensurate with the level of resilience required by the PNT user community.
2. PNT information is an asset, of critical importance, nationally and globally.
3. Multiple, interoperable technologies acting as a system of systems is the most likely approach to deliver the technology mix required for improving the resiliency of PNT services for users.
4. All aspects of PNT provision and use need to comply with applicable standards, laws, and regulations.
5. PNT applications and services need to use appropriate, proportional, and cost-effective security, secure by design, and be flexible enough to share and react to emerging threats and hazards.

[3] This is a hypothesised vision only and does not represent UK Government policy

6. Use of common terminology, definitions, and language across the PNT landscape to ensure a commonality of understanding and meaning, reducing confusion, especially for collaborative activities.

Regarding the technology portfolio noted, this must be addressed in a coordinated manner to contribute to a 'system of systems', and enabling the necessary resilient PNT services to meet user requirements.

When users have access[4] to resilient, robust, and diverse PNT sources[5], PNT services can be assured.

This strategic architecture also embeds requirements derived from users; it takes evidence on the threats and hazards that a resilient PNT system of systems will need to face and overcome; and, just as importantly it clearly captures the expected benefits provided.

Feeding into the strategic elements are the detailed description and understanding of PNT use cases, the analyses of these cases identify their criticalities and measurement criteria, referred to as Measures of Effectiveness (MOE)‒sometimes well known as threshold and objective criteria. The desired outcome is a well-understood and well-formed set of PNT User Requirements that can be used to derive PNT system-of-system requirements.

The strategic architecture must also consider the international PNT landscape, to enable collaboration, the LRS landscape now and in the future, and importantly the skills environment either within an enterprise or at a national level.

The strategic architecture can be documented within an organisation or programme as a PNT Management Plan which can be used as the basis for a delivery Programme Management Plan, an essential part of any capability delivery or R&D activity. It enables resources with the appropriate skills to be utilised at the right time, in the right manner to ensure maximum efficiency of resource management.

4.2 BUSINESS ARCHITECTURE

In many TOGAF implementations, the strategic and business architecture are often combined into a single grouping, however in our proposed architecture it is important and valuable to separate out strategy from the governance and delivery organisation to support a "zero-based approach" by, using the example of an Enterprise organisation, precluding current functions and structures from affecting the analyses and the development of the PNT architecture framework.

The business architecture defines how the strategy implementation[6] will be managed, its structure, governance, and business processes.

There are many organisational design and operating models that can be selected for the governance and structure for PNT coordination and management across an Enterprise. A structure will need to combine flexibility with being able to integrate into existing mechanisms and this paper proposes a model of a coordination function rather than a directing function. For

[4] This means that the services are available, not that the user must access them. Access to individual services is use case dependent based on specific need and risk profiles.

[5] Different PNT modalities

[6] In formal terms this is the business architecture for the strategic architecture.

this reason, for every Enterprise implementation, a Management (Programme) Board for PNT and a PNT (Management) Office is proposed as the necessary organisational governance to ensure a coordinated approach to PNT.

This PNT Office coordinates PNT activities across enterprises and can deliver vital oversight, guidance and coherence to the many delivery programmes that would normally operate in isolation. From an Enterprise perspective, this could be the first step in the development of a PNT services intelligent customer function. Figure 4 provides an overview of a proposed Enterprise PNT Office and its relationships with other entities.

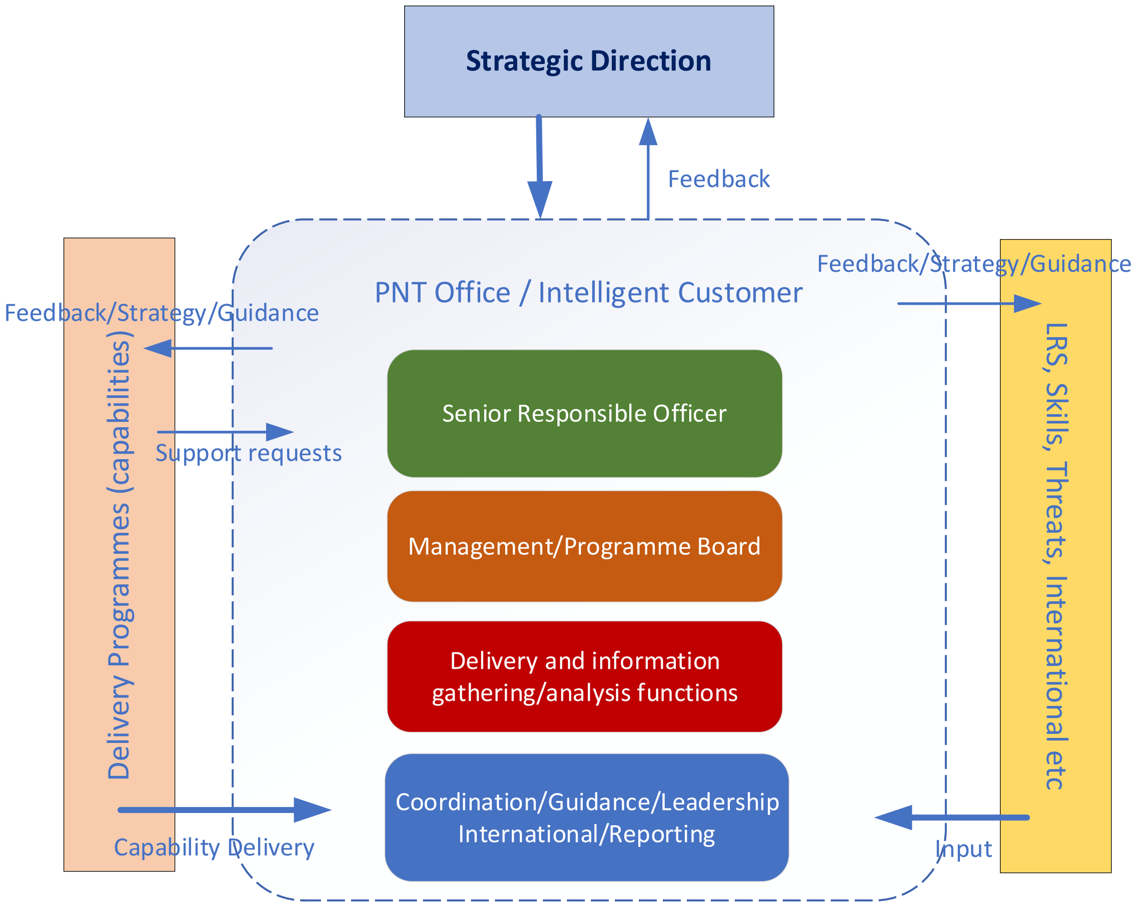

Figure 4: Proposed Enterprise PNT/Intelligent Customer organisation overview

To ensure the delivery of value for money and meet critical needs this body should provide the high-level integration of individual programmes; coordinate the interfaces and trade-offs between programmes, delivery departments and users, and provide the oversight necessary to ensure that the Vision is realised.

This approach is consistent with the direction taken by some nations and organisations where the understanding of dependence on PNT is growing. It does not replace individual delivery programme governance although there is clearly a role for it within those structures. It can also provide a central support and coordination across the enterprise and can share best practice and encourage reuse of architectural building blocks across domains/sectors.

Typical functions of this office, not exhaustive, are shown in Figure 5.

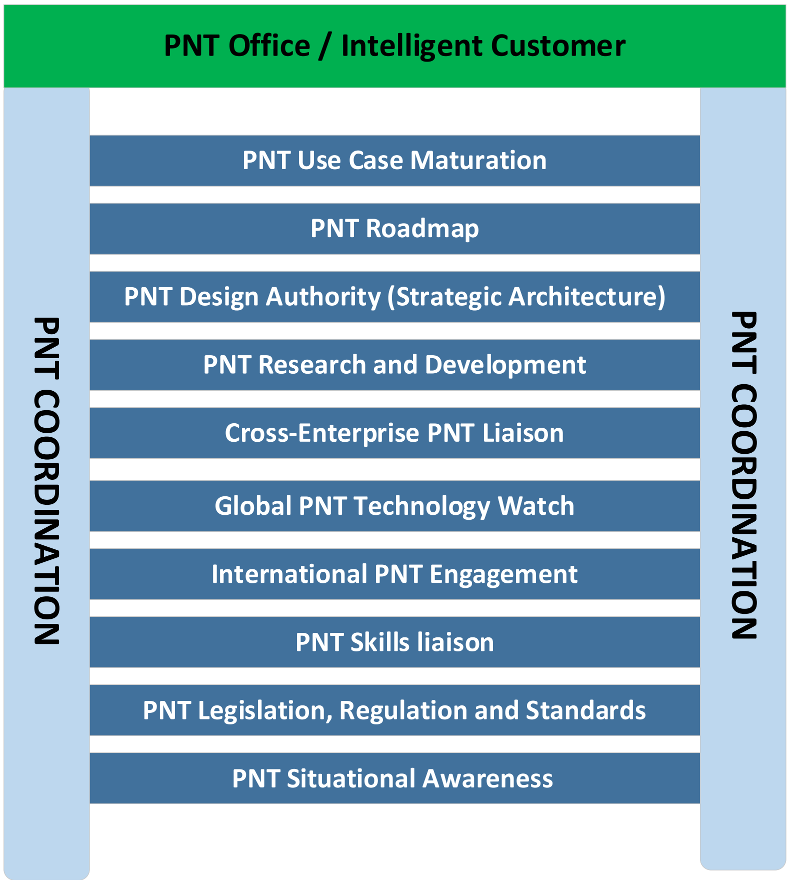

Figure 5: Example PNT Office functions

4.3 SERVICES ARCHITECTURE

The services architecture, also called the data architecture within TOGAF, identifies the overall logical and physical data assets and data management resources. For PNT this takes the form of a simple logic model showing the three key PNT functional areas, provision of PNT services, determination of PNT itself and then use of the PNT information. It also includes the core information exchange items between these logical segments. Finally, the enabling functions (PNT Office, enterprise processes, industrial capacity, supply chain etc) and security of the services are added which apply equally at all stages and across all segments in the logic model. (Figure 6)

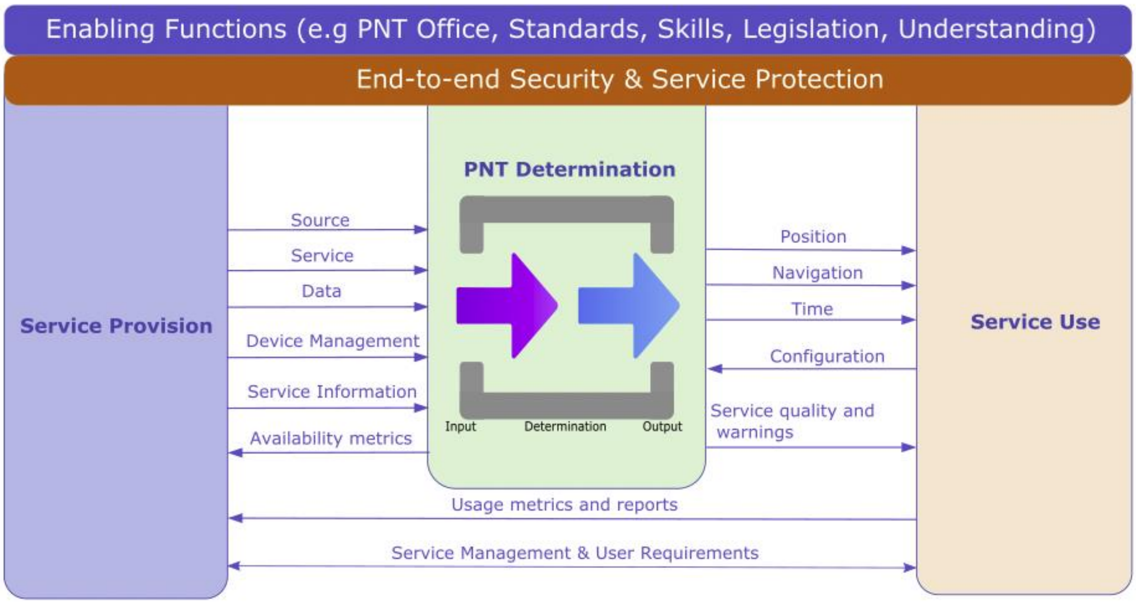

Figure 6: Architecture Framework Service Architecture

4.3.1 OPERATION OF LOGIC MODEL

How PNT data is provided to and consumed by the user is a key part of the model.

The *Service Provision* logic block addresses systems that can provide source information that enables the determination of PNT data, e.g., one-to-many[7] radionavigation signals, local high precision radio frequency sources or a fibre-optic distribution system of precise time. These systems or functions will normally provide information related to position, velocity, and time, often with data for device management or to augment the services provided.

PNT Determination logic can be directly related to user PNT equipment and is the central function in this logical chain, but it can be segmented into discrete functional areas:

- The PNT Input function can receive [raw] measurement information from multiple sources including external services and local sensing systems
- Determination converts raw measurements regardless of source, into useable PNT data in a format that the user can usefully consume. While it must be externally configured to provide the required service information to any external providers, this could be via an indirect route. The Determination function also takes in PNT data delivered to the user along with user configuration data and provides quality of service and alarm/warning information on the quality or availability of the data[8]. The logic considers that the consumption of PNT data is a service, as the user in effect has no in-depth concern for the detail behind how the data is acquired and determined, and only cares that it is received, appropriate, available, and resilient and has the possibility of being assured.
- The PNT output function provides PNT data and quality metric about that data to the user, in accordance with the user's control and configuration settings. PNT output data

[7] A broadcast system with one service to many users, e.g. GPS
[8] Also includes integrity, continuity

is generally used as the input to another process or function that facilitates the delivery of other user services or output (e.g. power distribution, broadcast television, machinery and/or vehicle control etc)

The *Service Use* logic block is where the user application(s) resides. It is a system-of-systems is its own right as PNT is only one input service used by the user application, to be combined with data and/or information from other systems, to determine or produce its final output. It is technology agnostic and can be used to set out terminologies, parameters, quality of service and functional structures at the application level. Ensuring the input PNT data into this stage is the key to a resilient (in terms of PNT) user application.

In many cases user applications may be safety or operationally critical and their degree of criticality can fundamentally depend on the underlying quality of the PNT information output by the PNT determination logical block.

4.3 TECHNOLOGY ARCHITECTURE

Within the architectural framework, capability and associated delivery risks and design authorities remain with the delivery programmes, however this paper proposes that the oversight of the technology mix and the risks associated with the provision of this holistic mix of capabilities resides and remains with the PNT [management] office. While the PNT office is not a capability delivery entity, it is the key to ensuring all-important establishment and continuing cross-enterprise/Government/sector coordination[9].

The PNT Office will also need to ensure it has access to the resources and skills to understand the technology mix, to ensure that an environment is created such that users have knowledge of and access to the required set of services, to ensure adherence to the architectural principles to deliver resilient, and where needed, assured, PNT. (see Figure 7: PNT Architecture Framework, Technology Architecture

below)

The system-of-system landscape consists of several, technology building blocks (the portfolio – or baseline) ranging from space to terrestrial to quantum based, each with differing strengths and weaknesses, but no common vulnerability. These building blocks may be at different stages of development therefore this hybrid concept may consist of existing operational systems, systems in development and those in conceptual phases. This enables a user to access sufficient, technologically dissimilar but interoperable services, such that their PNT data can be considered resilient against current threats and hazards and be adaptable to future threats, including those that can affect safety, security, and/or economic wellbeing.

Each technology (and use case) will have its own standards and norms that need to be accounted for in the portfolio. The Technology Architecture will determine candidate constituent members of the overall portfolio and identify gaps where research and development effort to mature or fuse emerging technologies, is needed.

[9] An important example being to assist user equipment manufacturers to understand the likely signal mix they will encounter to ensure there is equipment available to use the signals that services provide.

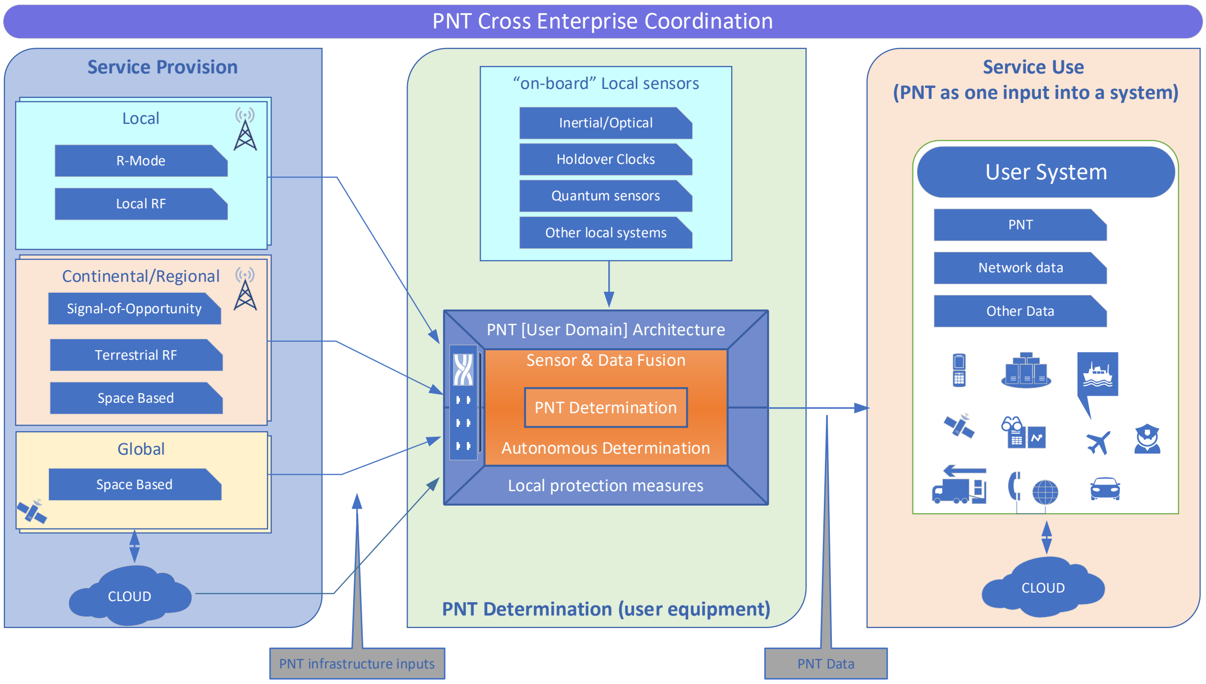

Figure 7: PNT Architecture Framework, Technology Architecture[10]

User Equipment is a critical element of this hybrid system of system-of-systems; it performs the functions of the actual PNT determination to identify where and/or when the user or asset is located. This function must be able to autonomously select which input(s) from external services, such as GNSS or terrestrial signals, to be the primary input or to augment/aid local sensing technologies. The combination of the external inputs, together with the selected integrated local technologies will, in each circumstance (use case), determine the degree of resilience obtained relative to that required.

Taking this hybrid approach, and aligning with MarRinav (MarRinav, 2020) findings, the technology architecture must support the hybridisation and fusion of PNT data types from different systems and sensing capabilities, including both terrestrial and space-based radio navigation and augmentation systems. By utilising multi-capability (system) user equipment and fusing with relevant local sensing such as inertial or visual, the resulting hybrid solution can assure the integrity of PNT for the user.

This hybrid SoS must remain technologically agnostic until use cases are overlaid. The assessment of the use cases is not in scope for this paper, but the output of that assessment will determine the most critical and complex use cases and indicate the complexity of the technology mix required to for a use case to have access to resilient PNT.

If a greater number of PNT sources are likely to be needed (to provide a higher resiliency or assurance for the user), this means an increasing overall complexity. If a system-of-systems is designed to meet the most stringent use case and applying that to all other use cases, it is likely to be over-specified/over-engineered, therefore a full understanding of what an SoS really

[10] Note: the "cloud" represented here refers to the ability for communications or data exchange through the internet or through closed/private cloud-based services

means in this context is needed, together with measures of performance for the individual capabilities and the overall technology mix.

4.3.1 PNT TECHNOLOGY ARCHITECTURE AS A SYSTEM-OF- SYSTEMS

This PNT technology mix, i.e., the sum of diverse and discrete parts (modalities), will deliver the necessary PNT services to users to ensure that enterprise and/or national/international interests are protected from PNT disruption. A system-of-systems for PNT can be visualised in Figure 8.

Figure 8: Multi-layer PNT Provision as a System-of-Systems

4.3.2 PNT SERVICE PROVISION

External (to the PNT determination entity) PNT services are multiple, independent, technologically dissimilar systems that are not managed centrally, with each system focussed on delivering its own outputs to deliver its own benefits. For example, a Space-based global system would deliver its services separately from a high precision self-contained local RF positioning service.

Some of these external sources could be service providers on a non-specific basis, but still contribute to the technology portfolio when viewed through the user (use case) viewpoint. This meets the criteria for a virtual system of systems (Table 1), having no central management capability and individual (not singular) goals. (Figure 9)

PNT providers are generally a one-to-many relationship (e.g. each GPS satellite or GNSS constellation serves billions of devices in a simplex mode of operation: GPS to User) therefore the multiple inputs from multiple signals come together in the user equipment which is the point where the internal logic decides which (one or all) of the inputs to use for PNT processing[11]. This is separate from the PNT service provision.

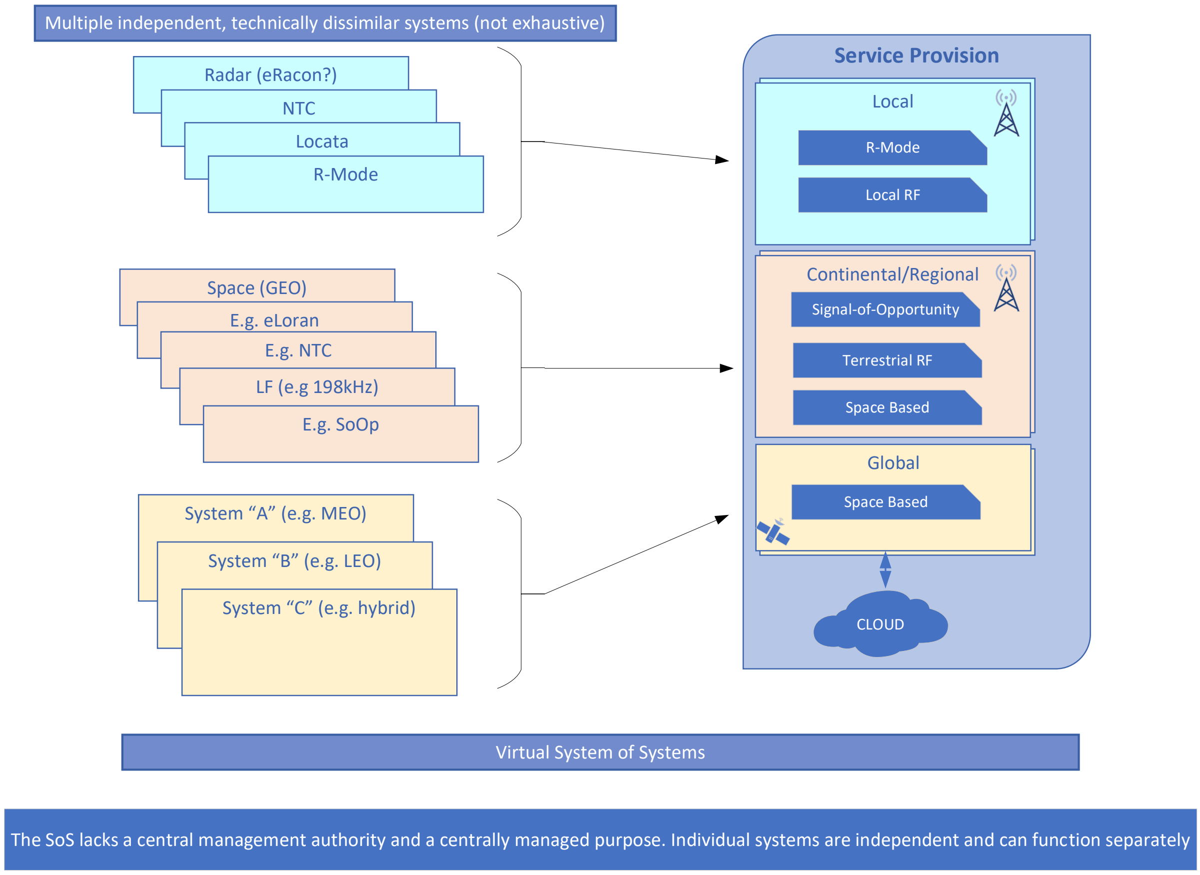

Figure 9: Service provision as a PNT System-of-Systems

4.3.3 PNT DETERMINATION

The PNT determination block can be mapped as a Collaborative SoS at the input to the function but an Acknowledged at the output of the function. (Figure 10) The selection of the specific input, data decoding, and fusing of different inputs into a position and/or time determination function (Kalman filter, least squares algorithm etc) fits the criteria for a Collaborative system of systems as defined in Table 1.

The constituent system (GNSS, terrestrial, "on-board" local sensing) is under the selectivity (i.e. are they used in the logic function) of the user equipment central processing function, but the constituents have a voluntary incentive to ensure that they interoperate. The user equipment has no power to enforce this interoperability, although it can provide a standard interface for data input.

[11] There are normally multiple inputs to the user device, but this may not provide resilience since there could be sharing of common failure modes

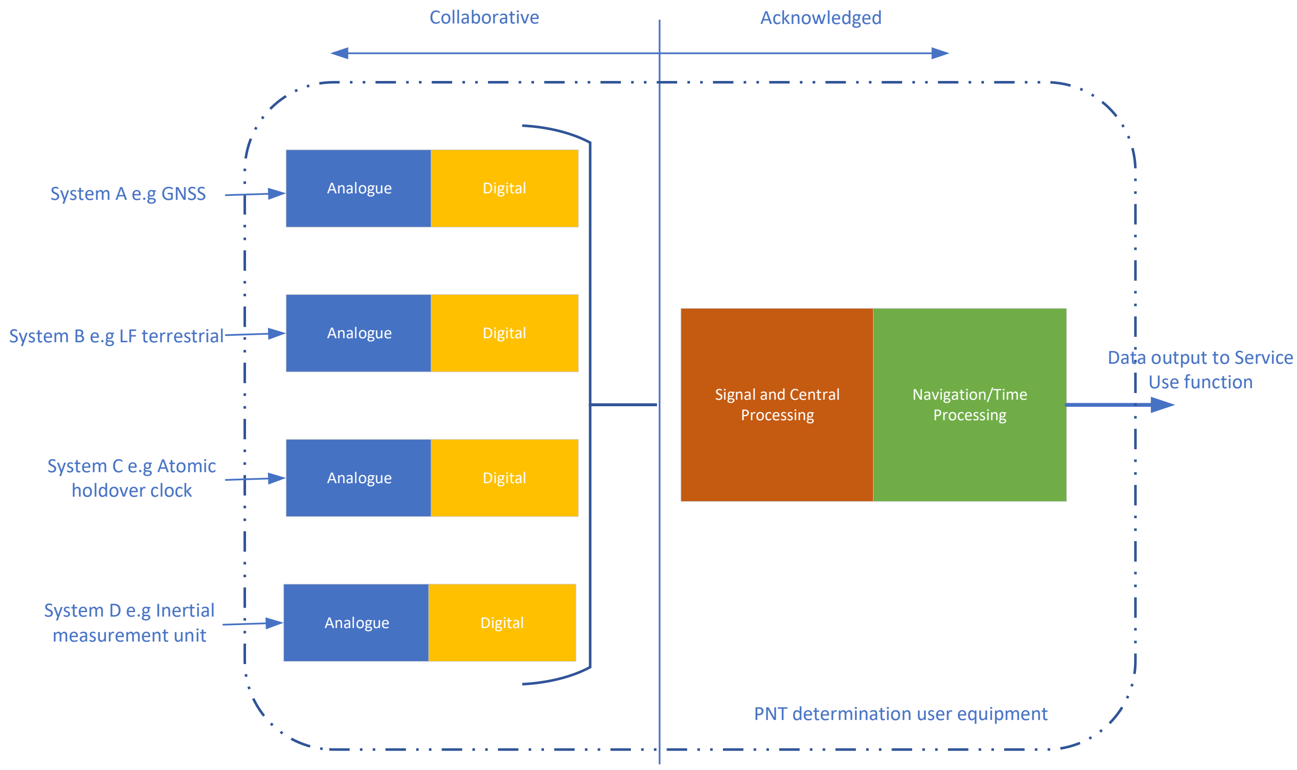

Figure 10: Collaborative v acknowledged system of systems in the user equipment

The output function can be mapped as an Acknowledged type of SoS. This is concerned with the maintenance of data protocols, data fusion and rendering the PVT/PNT output in the required form. Fusing the multiple sensor inputs together in the manner of an Acknowledged SoS ensures that the sensor systems retain their independence (each with strengths and weaknesses), but the processing functions have specific objectives (the output of resilient navigation and timing data), and processing resource, and will perform decision making to ensure the objectives are met.

Most modern equipment now uses, where necessary, multi-constellation GNSS[12] with perhaps a local sensing option. In the near-future terrestrial and local system technology will be blended in increasing tightness and complexity. Figure 11 shows this in the context of the previous diagram. (Figure 7)

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[12] It can be noted that multi-constellation GNSS can exhibit greater resilience than GPS only, but many implementations do not account for the common-mode failures that still exist unless technically dissimilar options are deployed.

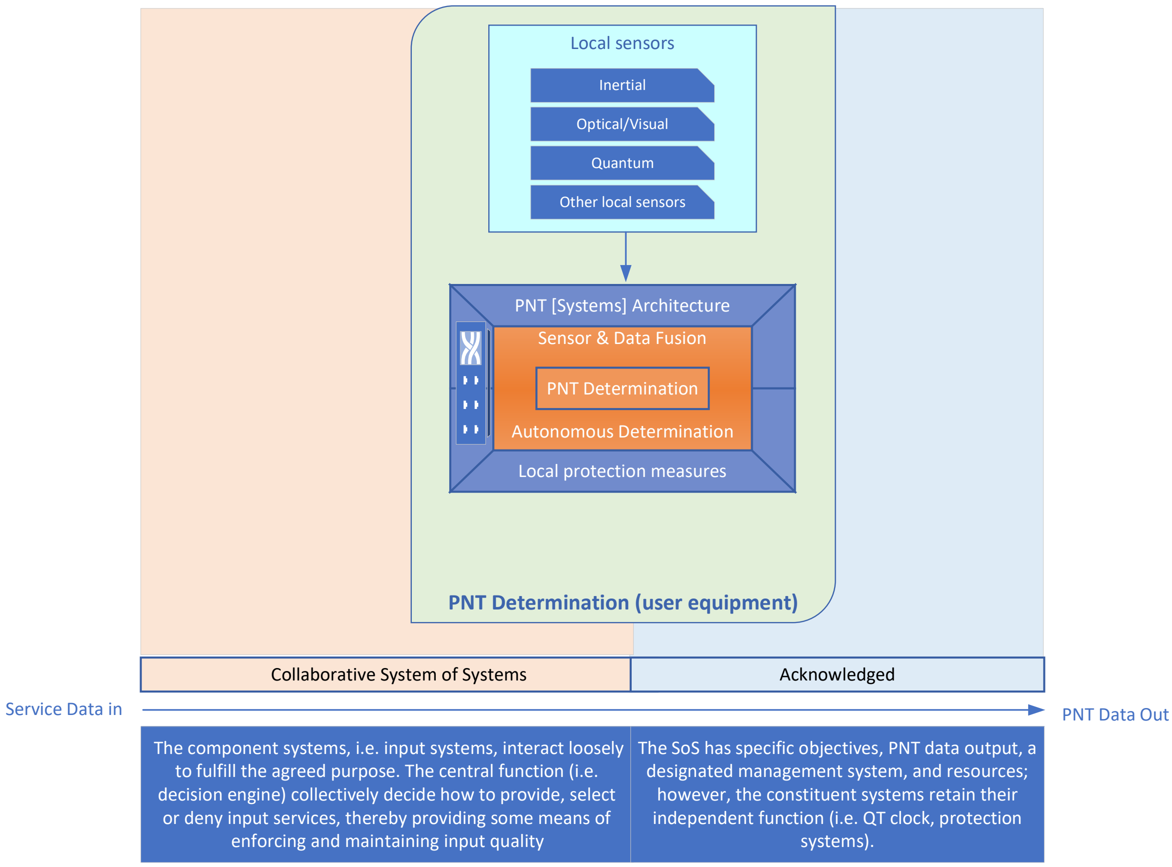

Figure 11: PNT Determination as a system-of-systems

4.3.4 PNT SERVICE USE

The purpose of the PNT determination function is to provide the PNT information to the user. The logical block that takes in this PNT data also takes in multiple complimentary (but possibly technically dissimilar) inputs, such as communications or machine control to fulfil its primary purpose. There is normally a dedicated process to manage and control the specific task fulfilling the user objective. This is the hallmark of a Directed SoS (Table 1) although in this case the dissimilar inputs do not often subordinate their normal operation to the central user process, Figure 12.

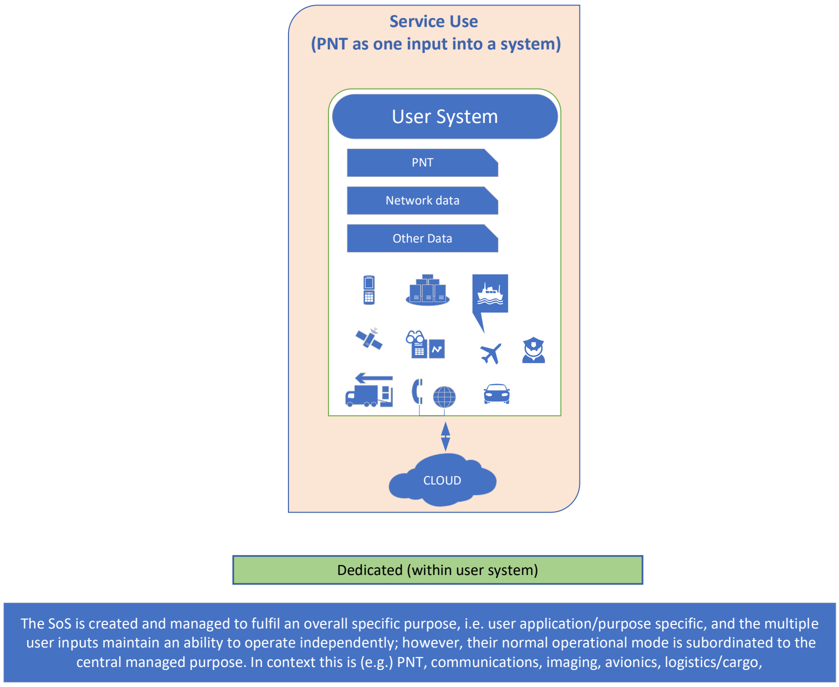

Figure 12: Use of PNT data within a system-of-systems

4.3.5 A FLEXIBLE PAIN FREE SYSTEM-OF-SYSTEMS

Using this SoS categorisation approach, we can consider the PNT environment from a complex systems point of view as multiple SoS types, each addressed, managed, and replaced as technology, threats, risks, and requirements evolve. This ensures that the factors within the seven-pain point model (INCOSE, 2015) of a system-of-systems are directly addressed, particularly where delivery of the overall system of systems capability is through multiple organisations and programmes.

Understanding the type of SoS at any stage in the technology model can improve common understanding, especially in terminology, and allow for the appropriate decisions to be made at the right time, in the right context by the right people.

Overall performance of the SoS is dependent on the performance of the individual constituent systems and their combined end-to-end behaviour, meaning that the framework does not address the details of the individual constituent systems, rather "it will define the way systems work together" (US Department of Defense, 2008)

4.4 DELIVERY – PNT SERVICE REALISATION

Realisation is all about delivery; delivery and deployment of operational capability, delivery of R&D programmes and the operations day to day of functional PNT services.

The relationships between existing capabilities (which are part of the system-of-systems service mix), research and development activities, and new candidate delivery programmes are shown in Figure 13, although the list of candidate programmes should not be considered exhaustive or expressing a preference.

The role of the PNT Office is clear in that it becomes a central focus for the overall ability to deliver access to sufficient PNT services for users to be resilient, allowing delivery/capability programmes to take care of their own requirements, and deliver against the specific benefits they offer, without being distracted by a wider agenda.

This part of the framework also accounts for "legacy" or existing capabilities and to the identification and coordination of R&D activities as the opportunity for shared costs or technologies may not be apparent except at the strategic level. This can guide R&D organisations to ensure skills and or technologies are available when needed.

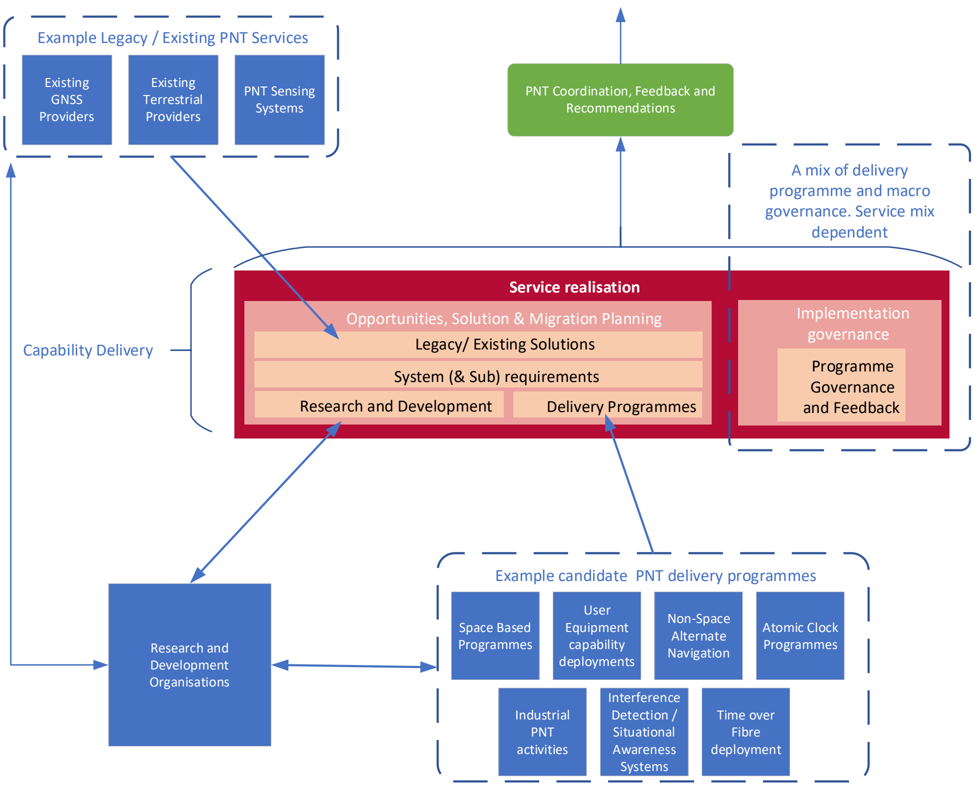

Figure 13: Relationships between realisation (delivery) entities

5. CONCLUSION

This paper has presented an architecture framework based on TOGAF principles, that is able to be used for the strategic and tactical management of the complex PNT environment to allow for services to be delivered coherently and that any vulnerabilities are identified, and appropriate action taken to maintain those services for users. The framework accounts for all aspects of policy, strategy, organisational design, and delivery methodologies, creating a structured approach that can be applied and managed through a system-of-systems approach.

The framework, should it be implemented, will introduce common terms of reference and metrics, denote a place for everything and how each part relates to everything else, allowing for decisions to be made at the right level, at the right time.

This PNT architecture framework will reduce overall enterprise fragmentation while preserving the independence of individual capability delivery functions yet will ensure that sufficient resilient and assured PNT services are available to those users who need them, reducing dependence on single points of failure. Overall, this framework allows for coherent strategic and tactical leadership, reducing organisational risk and lowering overall costs across an enterprise.

The role of the PNT Office is central to making this happen, particularly at the level of strategic requirements in ensuring that the technology mix can deliver resilient services, not just in the short term but also the long term as threats and hazards evolve. Research, development, and innovation are key aspects for the PNT office to coordinate, from which all delivery capabilities can benefit and still allow them to deliver against the specific benefits they offer, without being distracted by a wider agenda.

This proposed architecture framework is scalable and additionally allows for resources with very different skills, such as engineering v policy, threat management v regulation, to all work together understanding their focus with respect to the Vision, and making it happen.

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