A Novel
Generic Sensor Fusion Electronic Architecture Supporting Heterogeneous Commercial Sensing Technologies and Military Vetronics Systems

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Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree and does not incorporate any material already submitted for a degree.

Sean Murphy, 2023

Abstract

The aim of this thesis is to enhance local situational awareness for crews operating military land platforms within urban environments. Proposed is the utilisation of modern, automotive, Commercial off the Shelf (COTS) sensing technologies for applications within military land vehicles to enhance local situational awareness. Thus, improving crew, civilian, platform and mission survivability and safety in a cost-effective manner.

One current military area of operations is within diverse and complex urban environments, these operating environments can be described as Congested, Cluttered, Contested, Connected and Constrained (the 5C's). Outside the military environment, over the past 10 years significant advances within the automotive sector regarding sensing technologies and autonomous systems have increased exponentially. Driven by enormous investment from the commercial / private automotive Tier 1 and 2 suppliers, with recent years seeing many government sponsored, technology accelerator programs. The results of this significant global investment have produced low cost, advanced, sensing technologies and sensing capabilities, coupled with advanced sensor fusion capabilities, which could potentially be exploited within military land platforms to increase situational awareness.

This thesis looks to address the challenges faced by defence agencies by investigating and evaluating how the advancements in COTS sensing technologies can be taken advantage of to increase situational awareness for crews of Mounted Combat Systems (MCS) within chaotic urban environments. All outputs aim to support a cost-effective, rapid integration solution for current and future sensing technologies, harmonised with military land systems through a novel Generic Sensor Fusion Electronic Architecture (GSFEA).

The main contributions of the thesis are:

- First contribution: A detailed two-part study has been conducted to assess the applicability of COTS automotive sensing technologies and Advanced Driver Assistance Systems (ADAS) for use within military land platforms. Additionally, a detailed review of COTS integration into the military domain has been conducted, highlighting the barriers to COTS integration within military land systems.
- Second contribution: Utilising the results from the first contribution, a novel COTS sensing technologies classification concept (Commercial Technology Integration Levels (CTIL)) was developed. Along with a collection of novel, detailed, MCS COTS sensing technologies use cases, approved by the UK MoD. CTIL is a new evaluation framework and early de-risking tool that supports effective defence procurement strategies by evaluating the integration requirements for the rapid adoption of new capabilities and emerging technologies.
- Third, fourth and fifth contribution: The design and development of a novel Generic Sensor Fusion Electronic Architecture for integrating COTS sensing technologies with the current Def Stan 23-009 Generic Vehicle Architecture (GVA) and STANAG 4754 NATO Generic vehicle Architecture (NGVA).
- Sixth contribution: Verification and validation of the proposed solutions presented above through a complex testbed compatible with the GVA / NGVA. The results from this validation also provided a set of critical recommendations for the Def Stan 23-009 GVA, which have been reviewed by the United Kingdom's Ministry of Defence.

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The global pandemic impacted this research heavily in the final stages and contributed to a sizable delay in the completion of this work. Coupled with a significant personal trauma event that occurred at the same time as the pandemic resulted in one of the most difficult times in my life, thank you Yasmin Ysmenia Rivas Rivas for saving me.

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Finally, to my only daughter, Ms Gabriella Olivia Rivas Murphy. I love you. So much.

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Abbreviations and Acronyms

ADAS	Advanced Driver Assistance System
ADCU	Assisted & Automated Driving Control Unit
AEB	Autonomous Emergency Braking
ASIL	Automotive Safety Integrity Level
BBB	Beagle Bone Black
BMS	Battle Management System
CAN	Controller Area Network
CBR	Case Based Reasoning
CMM	Capabilities Management Module
CMOS	Composite Metal Oxide Semiconductor
COTS	Commercial-Off-The-Shelf
CPU	Central Processing Unit
CTIL	Commercial Technology Integration Level
DAS	Defensive Aids Suite
DBMS	Database Management Suite
DC	Direct Current
DDS	Data Distribution Service
DDSI	Data Distribution Service Interoperability
DPS	Digital Signal Processing
DSRC	Dedicated Short Range Radio
DVE	Degraded Visual Environments
ECU	Electronic Control Unit

EM	Electro Magnetic
EMI	Electro Magnetic Interference
FGCS	Future Ground Combat System
FMCW	Frequency Modulated Continuous Wave
GPS	Global Positioning System
GSFEA	Generic Sensor Fusion Electronic Architecture
GUI	Graphical User Interface
GVA	Generic Vehicle Architecture (Def Stan 23-009)
GSA	Generic Soldier Architecture (Def Stan
GBA	Generic Base Architecture (Def Stan
HDR	High Dynamic Range
HID	Human Interface Device
HMI	Human Machine Interface
HUMS	Health Usage and Monitoring System
IDA	Intelligent Digital Assistant
IDL	Interface Definition Language
IEC	International Electrotechnical Commission
IED	Improvised Explosive Device
IEEE	The Institute for Electrical and Electronic Engineers
IFV	Infantry Fighting Vehicle
INS	Inertial Navigation System
IO	Input Output
IOA	Interoperable Open Architectures
IR	Infrared

ISO	International Organization for Standardization
ITS	Intelligent Transport System
JDL	Joint Directors of Laboratories
LAAS	Laboratoire d’Analyse et d’Architecture des Syst`emes
LDM	Land Data Model
LED	Light Emitting Diode
LIDAR	Light Detection and Ranging
LOSA	Land Open Systems Architecture
LRR	Long Range Radar
LSRG	Land Systems Remote Gateway
MCC	Mounted close Combat
MCS	Mounted Combat System
MiLVA	Military Vetronics Association
MOD	Ministry of Defence
MOE	Measure of Effectiveness
MOP	Measure of Performance
MPEG	Moving Picture Experts Group
MFL	Multi-Function Camera Lidar unit
NCAP	New Car Assessment Program
NGVA	NATO Generic Vehicle Architecture
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
OMG	Object Management Group
OO	Object Oriented

OODA	Observe Orientate Decide Act
PAL	Phase Alternating Line
PC	Personal Computer
PCM	Pulse Compression Modulation
PTP	Precision Time Protocol (IEEE 1588)
RADAR	Radio Detection and Ranging
RCS	Radar Cross Section
RGB	Red Green Blue
RPG	Rocket Propelled Grenade
RTI	Real Time Innovations
RTOS	Real-Time Operating System
SIMILAR	State Investigate Model Integrate Launch Assess Re-evaluate
SoS	Systems of Systems
SPI	Serial Peripheral Interface
SRR	Short Range Radar
SUGV	Small Unmanned Ground Vehicle
SWAP	Size Weight and Power
SWOT	Strengths, Weaknesses, Opportunities and Threats (analysis)
TARDEC	Tank Automotive Research, Development and Engineering Centre
TCP/IP	Transmission Control Protocol/Internet Protocol
TMS	Traffic Message Channel
TRL	Technology Readiness Level
TTL	Transistor-Transistor Logic
UART	Universal Asynchronous Receiver Transmitter

UAV	Unmanned Air Vehicle
UDP	User Datagram Packet
UGV	Unmanned Ground Vehicle
UK	United Kingdom
UML	Unified Modelling Language
UOR	Urgent Operational Requirement
UPNP	Universal Plug and Play
US	United States
USB	Universal Serial Bus
V2X	Vehicle to Everything
V2V	Vehicle to Vehicle
VGA	Video Graphics Adapter
VPN	Virtual Private Networking

List of Publications and Presentations / Workshops

Published Papers

To support the contributions within this body of work the following publications were written. Primarily these papers were accepted within peer reviewed IEEE conferences:

S. Murphy, E. Stipidis, and P. Charchalakis, "Utilisation of Automotive Commercial Sensing Technologies within Military Land Systems to Increase Survivability," in 2019 International Conference on Military Technologies (ICMT), 30-31 May 2019 2019, pp. 1-8, doi: 10.1109/MILTECHS.2019.8870068.

Technical reports

DSTL technical report upon completion of a 2-year DSTL funded research program:

Exploitation of Automotive Technologies, Technical Report, DSTL/AGR/00723/01.310118.WP3, DSTL/AGR/00723/01: - Crew Systems Research, Release Date: 31st Jan 2018 Classification: UK OFFICIAL SENSITIVE.

Defence Standard Contributions

Due to the unprecedented global situation over the last few years during the COVID pandemic the completion of this thesis was delayed. This delay in turn provided an unusual insight (for research) into the real-world influence from this body of work.

Examples of the impact from this body of work, either directly or indirectly, can be seen within the UK MoD Def Stan 23-009 Part 1 Issue 4 Generic Vehicle Architecture (release date 14 July 2019). Notably, the inclusion of Precision Time Protocol (PTP) within Def Stan 23-009 GVA Part 1 and the significant expansion of Def Stan 23-012 Part 1 Issue 1 (release date 28 October 2020) Generic Soldier Architecture. Details of which can be found within Chapter 8, Conclusions and Future Work.

Workshops / Presentations

The following working groups were attended by invitation due to the nature of the research topic:

Military Vetronics Association (MiLVA), NGVA Data Model Working Group Meeting, Topic: Data Infrastructure, 5th – 6th March. 2019, Huizen, Netherlands.

Generic Vehicle Architecture Data Model Working Group (GVA DM WG) meeting on the 24th – 25th April. 2019, Swindon, United Kingdom.

Open Days

Many open days and presentations to industry within the VRC research centre during the course of the research, examples of companies that attended include RTI, Continental AG, Thales, UK MoD (DSTL, Army HQ and DE&S).

Real Time Innovations, Inc® Promotional Research Brief

A short paper highlighting the research conducted utilising RTIs implementation of DDS.

https://www.rti.com/hubfs/Collateral_2017/University_Program_Snapshots/rti-university-program-brighton.pdf

1 Introduction

The current and future operating environment for military land systems is likely to be a complex urban environment, as set out in the United Kingdom (UK) Ministry of Defence (MoD) strategic trends [1, 2]. This operating environment can be described as one or more of the following states, Congested, Cluttered, Contested, Connected and Constrained (the 5C's). The following descriptions provide the context for these terms:

- **Congested** – An environment which contains activity from multiple sources simultaneously, be that civilian, commercial and / or military. This can be in the form of population, public transport, cyber space or the electromagnetic spectrum.
- **Cluttered –** Can be described as an environment which prevents the ability to effectively identify individuals, items or events, especially if the environment is also congested.
- **Contested –** This describes the nature of the environment often engaged allied forces can be facing multiple minor factions / non-state actors that can be in competition or conflict with each other. The ability to recognise and identify the subtle differences can be critical to the safety of crews or mission success.
- **Connected –** This term refers to the ever-increasing connectivity within urban environments, saturation of wireless signals, mobile devices in populated areas through to connected transports systems. The threat for operating environments to be deliberately disconnected remains, which in turn, can create a congested or cluttered environment as population or public infrastructure responds to any disruption.
- **Constrained –** This term refers to the constraints of morality within UK military operations (protecting civilians for example), however potential threats often are not so constrained and could operate without such constraints.

Such environments present additional challenges for providing enhanced situational awareness for the crews of military land vehicles.

As crews of military land platforms are forced to often operate 'under armour' (within the confined and highly protected armoured vehicle), their local situational awareness is greatly limited in many conventional armoured vehicles. This decreases the crew's ability to make informed decisions in a timely manner; especially in noisy, congested and cluttered environments as described above. The threats faced by crews of Mounted Combat systems (MCS) is often asymmetric, hidden in a cluttered backdrop and undercover amongst civilians, which is in contrast to historically open battle spaces for large scale warfare (i.e. main battle tank versus main battle tank). This increases the complexity of the operating environment and results in what is known as an ‘empty battlefield’, where the enemy is present but is extremely difficult to detect. Furthermore, such environments are anticipated to be dynamic and fluid (e.g. adversaries creating roadblocks to force crews to take a compromised route) [3, 4]. Accordingly, the situational awareness system needs to support the analysis of change in the space-time dimensions, for example integration of intelligence gathering and atmospherics change detection.

These challenges highlight the increasing need for crewmembers’ operating manned land systems to have intimate knowledge of their surrounding environment. Local Situational Awareness (LSA) systems have traditionally been used in military vehicles for the primary function of firepower (target acquisition and weapons control). However, as the operating environment is becoming increasingly complex, there are pressing needs to use situational awareness systems for the safe operation of the vehicle (e.g. driving / manoeuvring, turret actuation, etc.), and for the identification and detection of threats, in particular close-proximity asymmetric threats.

Outside of the military environment, the automotive industry has been investing enormous resources into vetronics systems development over the last decade due to the growth of autonomous vehicle technology [5]. The research and development of low cost, high performance, COTS sensing technologies is currently at unprecedented levels. It could be said modern fully autonomous vehicles (level 5) not only ‘know’ (situational awareness) their environment in high detail but also understand the context of their current and near future (prediction) environment [6, 7].

In addition, given the commercial automotive industries extremely competitive nature these technologies can offer opportunities to support cost-effective situational awareness applications within military land platforms. It is envisaged that such technologies could potentially be exploited within Mounted Combat Systems (MCS) to enhance situational awareness and improve safety for crews of military land platforms operating in complex urban environments, thereby increasing crew and platform survivability. Automotive technologies such as active safety systems, driver assistance, object / pedestrian / cyclist detection and dynamic route navigation are developed for use in complex urban environments. It is anticipated that the fusion of sensory information and the automation of some intense / tedious tasks are likely to provide a tactical advantage for engaged forces.

Finally, research undertaken by various defence agencies indicates that to maintain tactical advantage in diverse, complex and rapidly changing theatre of operations Commercial of The Shelf (COTS) integration / harmonisation with military vetronics is required [8-11]. Such procurement strategies enable rapid adoption of new technologies as well as providing cost effective procurement of new / enhanced capabilities within military land platforms.

The primary purpose of this research is to provide the crews of MCS with enhanced situational awareness of the local environment therefore increasing crew / MCS survivability. Additionally, civilian safety will also be increased given the area of operations are most likely to be and often are currently, civilian populated urban environments as discussed previously.

The general meaning for the term situational awareness as described by Endsley [12] is "knowing what's going on" and, the authors formal description, "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future".

This research is concerned with investigating firstly, how autonomous machines (civilian vehicles, robotics etc.) have been provided with their local situational awareness (utilising sensor fusion, generally for safe navigational purposes). Secondly, *"if"* and *"how"* this can be integrated within the unique constrained environment of military land platforms vetronics to provide crews of MCS with enhanced survivability by allowing them to have an enhanced understanding of their local environment.

There has been evidence provided by the UK MoD of vehicles being disabled / damaged by the simplest means or friendly forces being injured within base of operations during vehicle manoeuvres. This is attributed to the crew having a severely limited visibility of external events outside of the land platform, such as:

- Persons approaching the vehicle, pouring petrol over the vehicle and setting the vehicle on fire, potentially making the vehicle unavailable for days.
- Asymmetric (unusual or unknown) threats targeting the vehicle from high vantage points or from within a crowd of civilians within a confined urban environment.
- Inability of military vehicle technology to be able to identify Improvised Explosive Device (IED) often recently buried within the road or to the side of road.
- Civilians in close proximity to vehicle going about their day-to-day life.
- A high percentage of injuries to military personnel occur whilst vehicles are moved within base of operations for maintenance, repairs, refuelling or storage and so on.

All the above challenges either place the vehicle crew or local civilians in danger, these challenges have become prominent due to the fact that the battlefield environments have changed dramatically within the last three decades. They are rarely large open spaces or battlefields, increasingly areas of operations and cluttered and chaotic urban environments as stated previously. Figure 1.1 below shows an example of the type of environments being described, highlighting the obvious dangers for crews operating MCS and the safety risks to civilians and civilian infrastructure local to the area.

Figure 1.1 Lancs patrol - Basra 2007 [13]

1.1 Thesis Objectives

This research intends to answer the following questions:

1. Can the current advancements in Commercial off the Shelf automotive sensing technologies be leveraged to enhance MCS crew’s local situational awareness thereby cost effectively increasing safety within UK and NATO military land platforms?
2. What are the non-technical barriers to the integration of automotive COTS sensing technologies within military land systems and how can these be addressed?
3. What are the technical barriers to the integration of automotive COTS sensing technologies within military land platforms and how can these be addressed?

The hypothesis is that the current advancements in automotive sensing technologies can be used to increase safety and enhance survivability for crews (operating) and civilians (within local proximity) of UK and NATO military land systems in a cost-effective manner.

Therefore, the objective of this thesis is to enhance the local situational awareness for crews operating military land platforms within urban environments. Proposed is the utilisation of modern, automotive, Commercial off the Shelf (COTS) sensing technologies for applications within military land vehicles to enhance local situational awareness. Thus, improving crew, civilian, platform and mission survivability and safety. If the above high-level objective is achieved, crew, civilian, platform and mission survivability and safety could be increased.

The technical objectives to achieve the aims described above are to not only support the Interoperable Open Architecture (IOA) [14] approach to systems architecture design, but to also provide a solution for the integration of commercially available sensing technologies with current and future military land platform vetronics. Additionally, this thesis will also (where possible) consider and document the performance benefits versus the cost implications to the UK MoD when addressing the above technical objectives.

In order to meet these objectives, the thesis achieved the following:

1. An extensive review and analysis of modern sensing technologies, analysing their sensing characteristics and their communication technologies. Assessing their applicability to mounted combat systems by providing use cases, this analysis:
    - Provided a study of automotive sensing technologies sensing parameters / attributes,
    - Provided a study of Advanced Driver Assistance Systems (ADAS),
    - Provided a study of automotive sensing technologies communication protocols,
    - Developed use cases for sensing technologies within the military context for multiple land platform types / roles,
    - Identified the challenges to be met within this unique domain for integrating COTS technologies form a procurement perspective,
    - Provided a set of results which were utilised in the formulation of the Commercial Technology Integration Levels (CTIL) described below to address the challenges described above.

2. To design a framework for the classification of candidate COTS sensing technologies, Commercial Technology Integration Levels (CTIL). Designed to reduce risks for defence procurement agencies when attempting to select and assess COTS technologies for integration with military land platforms, this framework:
    - Provides a structured method for the classification of COTS technologies integration profiles,
    - Provides early identification of integration costs, such as: time, effort required.
    - Provides early identification and indications of capability aspirations in comparison to the cost of integration,
    - Presents a preliminary set of case studies highlighting the CTIL behaviour and operation,
    - Has been validated utilising the results from the case study described above.

3. To develop a Generic Sensor Interface Architecture (GSIA) for heterogeneous automotive buses integration with DefStan 23-009 Generic Vehicle Architecture, this sensor interface architectural approach:
    - Harmonised automotive COTS sensing technologies with Def Stan 23-009 Generic Vehicle Architecture,
    - Has been implemented within a diverse and complex Generic Sensor Fusion Testbed to allow the creation of statistical network performance data sets,
    - Has been validated by examination and statistical analysis of the sensor performance in multiple environments data sets,
    - Provided complex data to be used for the validation and verification of the Generic Sensor Fusion Electronic Architecture (GSFEA) approach presented within the subsequent work,
    - Provided a comprehensive performance analysis of OMG DDS profile, validating sensor network performance when creating a sensor node interface.

4. To design novel Generic Sensor Fusion Electronic Architecture (GSFEA) with multimodal capabilities compatible with the DefStan 23-009 Generic Vehicle Architecture. This has been developed to address the unique challenges of the military vetronics environment. The architectural design:
    - Provided the high-level requirements analysis for a GSFEA for the GVA environment,
    - Provided novel multimodal sensor fusion process management to meet the unique requirements of the military domain, capabilities verified by experimental processes and validated against published literature,
    - Is modular in design allowing rapid reconfiguration verified through experimental processes utilising the work completed within goal three above.
    - Provided a Data Distribution Service (DDS) Quality of Service (QoS) profile derived through experimentation and empirical analysis,
    - Provided a novel approach to system management services for the battlefield environment and message temporal synchronisation utilising IEEE 1588 Precision time Protocol (PTP),
    - Provided a comprehensive performance analysis of OMG DDS profile, validating sensor network performance when coupled with the GSIA designed and presented within objective three above.

5. To validate the Generic Sensor Fusion Electronic Architecture (GSFEA) utilising a complex, diverse generic sensor fusion testbed compatible with the current DefStan 23-009 Generic Vehicle Architecture. This testbed was designed to provide the following:
    - A complex network infrastructure,
    - Multiple processing units of varying configurations,
    - A rapidly reconfigurable electronic architecture to support multiple testing approaches / methodologies,
    - The ability to validate all designs and implementations of the proposed frameworks within this thesis,
    - Recommendations to the UK MoD Generic Vehicle Architecture Land Data Model (GVA LDM) working group.

1.2 Thesis Structure

The remainder of this thesis is arranged as follows, combining six discrete contributions:

Chapter 2 is the first background chapter.

It describes high-level approaches adopted by the current evolving defence standards relevant to this thesis, highlighting why they approach integration with the IOA ethos. Chapter 2 also examines military land platforms' data management infrastructure which provides sub-system communication management and data availability throughout the platform. The future direction of DefStan 23-009 Generic Vehicle Architecture is also discussed.

Chapter 3 is the second background chapter and related works.

Describes historical high-level sensor fusion logical models and moves forwards towards current sensor fusion frameworks discussed within recent literature, critically discussing the benefits and constraints of these models. Further to this, common sensor fusion architecture topologies are discussed which provide increased detail of sensor fusion framework structure and behaviour when implemented. Additionally, Chapter 3 then provides a basic overview of common automotive bus technologies that are applicable to this work. Finally, related work and future trends are also presented here to provide context and analysis.

Chapter 4 is the first contribution chapter.

Presents a two-part study for the applicability of commercial automotive sensing technologies within military land platforms. The results of the studies carried out provided an understanding of "*if*" COTS technologies could be applicable to Mounted Combat Systems (MCS) and inform "*how*" these technologies could be exploited within MCS. The critical arguments of the thesis are also presented here highlighting the need for a resilient generic sensor fusion architecture if COTS sensing technologies are to be effectively exploited within MCS. Finally, specific use cases were developed to demonstrate how this knowledge could be used to enhance local situational awareness for crews operating MCS, which have been evaluated and accepted by the United Kingdom Ministry of Defence.

Chapter 5 is the second contribution chapter.

Based on the results of the studies presented within Chapter 4, a framework to support defence procurement agencies in the selection of complex COTS technologies has been developed. The goal of the framework is to provide indications of cost, time to integrate, integration characteristics versus capabilities gained to mitigate risks during the procurement stage of COTS technologies. The Commercial Technologies Intergradation Levels (CTIL) framework is provided as an early de-risking tool to support defence procurement decision making during the technology selection phase, a study is provided within this chapter demonstrating the framework based on a selection of sensing technologies and a selection of ADAS safety sub-system.

Additionally, a collection of novel COTS sensing technologies use cases were developed for the military domain. The focus of these use cases is to address specific challenges faced by MCS crews operating within an urban environment by utilising COTS sensing technologies in novel ways to increase situational awareness or improve safety. These use cases were reviewed and approved by the UK MoD.

Chapter 6 is the third contribution chapter consisting of three independent contributions combining into the GSFEA architecture.

It presents a novel multi modal Generic Sensor Fusion Electronic Architecture (GSFEA), designed to meet the current and future requirements for crews of Mounted Close Combat in the modern battlefield environment. The framework provides novel methods for meeting the unique requirements found within the military domain by the realisation of a modular sensor fusion approach providing novel capability management of sensor sets. Additionally, a novel Generic Sensor Interface Architecture (GSIA), designed to provide the integration of heterogeneous sensing technologies with the DefStan 23-009 Generic Vehicle Architecture has been developed. Additionally, a novel Capability Management Module (CMM) which provides the data management services and message synchronisation is presented. Finally, the Land Systems Remote Gateway (LSRG) is presented, describing an architecture design to enable future LOSA The Internet of Battlefield Things (IoBT). Together these three components complete the GSFEA design. Critical security requirements and off platform communications are also addressed here. Finally, it is shown how system modularity and real time reconfigurability (system management for the battlefield environment) can be used to address the unique challenges of the military land systems domain. Thus, enabling the exploitation of COTS sensing technologies within Def Stan 23-009 GVA compliant land systems for enhanced situational awareness.

Chapter 7 is the fourth contribution chapter.

It presents a diverse and complex DefStan 23-009 GVA compatible testbed, developed as a tool for the verification and validation of the design presented within Chapter 4, Chapter 5 and Chapter 6. The analysis of the results from all of the experiments carried out to verify the GSIA design and the GSFF designs are presented here. Security solutions and analyses are examined here through experimental processes. Also described are the preliminary conclusions derived from the results of not only verifying both architectural designs but also verifying the use cases presented within Chapter 4 and Chapter 5.

Chapter 8 presents the final discussion regarding the findings of this work and concludes the thesis. Recommendations were provided, reviewed, and accepted by the GVA / NGVA working groups. Additionally, due to the recent pandemic creating delays with the completion of this thesis, unusually, the real-world impact from components of this body of work can be seen within the defence standards relative to this work and is also presented here.

Finally, recommended future work is also discussed and presented here.

2 Military Vetronics Architectures and Standards

2.1 Introduction

This chapter provides an overview of the current standards that are relevant to this thesis within which this research has been carried out. The concepts of Interoperable Open Architectures (IOA) are introduced describing how and why the IOA paradigm is closely related to the goals of Land Open Systems Architecture (LOSA) which contains the Def Stan 23-009 Generic Vehicle Architecture (GVA), Def Stan 23-012 Generic Soldier Architecture (GSA) and Def Stan 23-013 Generic Base Architecture (GSA) which informs the work presented in further chapters.

The relevant sections of Defence Standard 23-009 Part 0, Issue 4, Generic Vehicle Architecture, GVA Approach and Defence Standard 23-009 Part 1, Issue 3, Generic Vehicle Architecture, GVA Infrastructure are presented, along with other various open standards. This discussion provides the reference for the work completed within many sections of this thesis, whilst also informing the requirements analysis and design process of much of the research presented within this body of work.

Given the unique domain of military vehicle electronics (vetronics, encompassing everything from processing data to network infrastructure) the following sections describe the approach taken by the UK MoD to support and guide the design and verification of military land platforms and integration of their sub-systems.

2.2 Vetronics and Vetronics Integration Approaches

2.2.1 What is Vetronics

The term vetronics **(Ve**hicle elec**tronics)** is the vehicular equivalent of avionics (**avi**ation electr**onics**) and is a term used to describe all components of vehicular electronic systems / sub-systems. This encompasses Electronics Control Units (ECUs), power harnesses, Human Machine Interfaces (HMI) and network protocols.

Modern automotive vetronics systems comprise of 70 or more ECUs, networked together to provide comfort, safety, infotainment and system information (i.e. drivetrain, engine management). As innovation continues to increase so does system complexity which in turn has prompted new approaches to reduce complexity whilst increasing functionality [15]. Figure 2.1 below describes this effect detailing the growth of ECUs within modern commercial vehicles throughout the last sixty years with predictions of future trends that are now beginning to be developed (this is discussed in further detail within Chapter 3, section 3.5.1 Software Defined Vehicle).

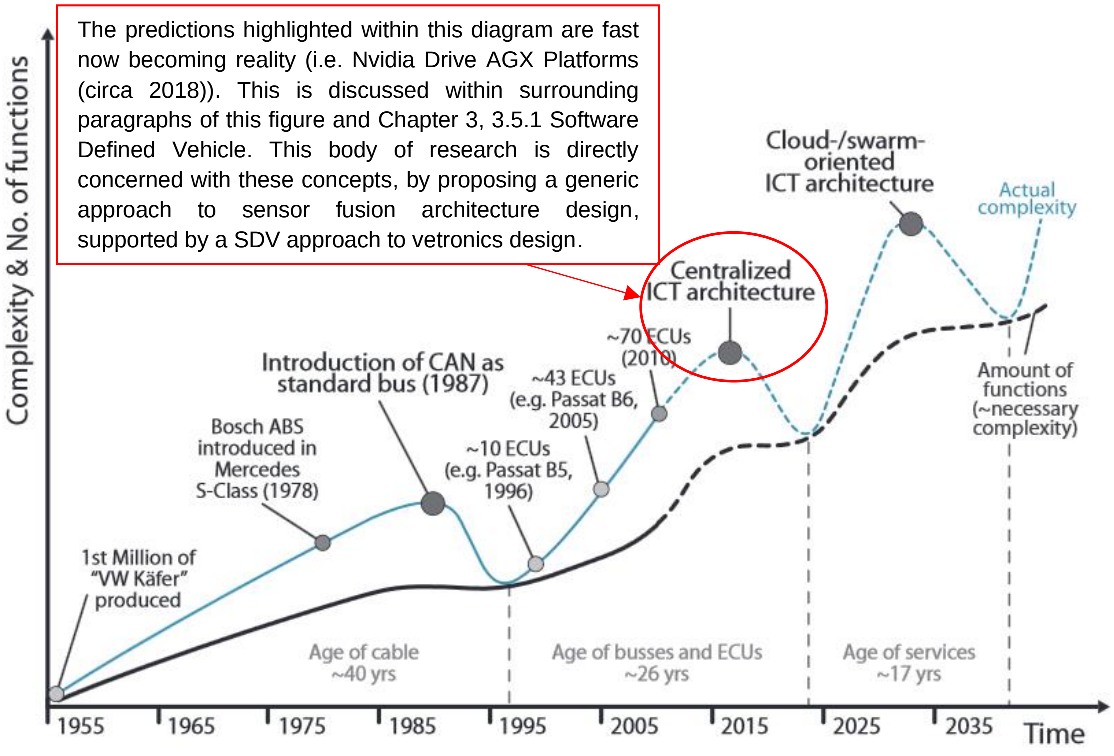

Figure 2.1 Evolution of Vetronics function and complexity (modified to highlight key points) [15]

The recent advancement of functionality driven by increasing demands for semi-autonomous assist functions within the modern automotive industry, have driven new innovations to be able to cope with increasing requirements for computational processing power whilst reducing the need for even more disparate, smaller, ECUs. Nvidia Corporation for example have been developing High Powered Computing (HPC) platforms such as the Nvidia Drive AGX Platforms [16] coupled with open source software stack promoting innovation / growth and vendor independence within the autonomous vehicle space.

2.2.2 Interoperable Open Architecture

Interoperable Open Architecture as discussed by HEE et al. [17] and also within a white paper published by Real Time Innovations (RTI) [14], is a base architecture (as in a reference architecture, not to be confused with base of operations) design approach. The IOA approach is designed to support interoperability between components and sub-systems that perhaps have been designed by many different system integrators (suppliers). Thus, supporting cost-effective through life upgrades whilst reducing vendor lock in, creating a flexible vehicle base architecture design approach using common open standards and interfaces where appropriate. This is in direct contrast to the (now in the process of being superseded by IOA) 'bolt on approach', where land platform sub-systems were primarily stand alone, proprietary, end to end implementations.

The IOA design approach is adopted within the military domain for current and future military land platforms. The current United Kingdom (UK) land platform defence standards (that this research is concerned with) to apply this approach are defined within the Def Stan 23-009 Parts 0, 1, 2 and 3 GVA [18-21] and the (NGVA) NATO Generic Vehicle Architecture [22]. These standards define the guidelines for vetronics (vehicle electronics) sub-systems design with regards to power and data infrastructure to aid integration within new and existing land platforms.

Aligned with the GVA approach, Land Vehicles Open Systems Architecture (LAVOSAR) [23] has been developed and investigation carried out for the integration and development of mission systems within vehicles, attempting to follow the same ethos as described by the IOA approach.

Additionally, there has been a change of direction for UK MoD procurement practices within the last two decades [10] [11]. It has been identified by various defence agencies that to maintain tactical advantage in diverse, complex and rapidly changing theatre of operations Commercial of The Shelf (COTS) integration/harmonisation with military vetronics is required [8] [9]. Such a procurement strategy enables rapid adoption of new technologies as well as providing cost effective procurement of new / enhanced capabilities within military land platforms.

2.2.3 Open Systems Architecture Approach for Military Land Systems

Typically, any military product, technology or sub-system to be used within battlefield conditions is expensive, proprietary and is expected to be in service for a decade or more. The operating environment is considered to be harsh and these systems are designed accordingly, however, the financial cost and the time to deployment can be significant to meet these requirements.

Utilising proprietary systems with an expected long-term life cycle of a decade or more (typically military land systems can be in service for forty years with incremental upgrades) promotes the condition of being tied to a specific vendor for the entire product life cycle. This leads to additional costs when for example seeking to add or modify existing capabilities, compound this with the rapidly changing battlefield of the last two decades new, strategies and approaches to military system design and procurement have been developed [24].

These developments are an attempt to mitigate ‘vendor lock in’ a term used to describe the effect of utilising closed proprietary systems with a reliance on the original vendor throughout the entire life cycle of the product. The ability to move to another vendor for a similar or improved service / capability is diminished due to incurring substantial additional costs [25]. Therefore, the move towards open systems architecture approach has been adopted by the UK MoD to promote competition, reduce costs and improve availability of capabilities services and upgrade paths for future military land systems.

2.3 Defence Standard 23-009 Generic Vehicle Architecture

This section provides a brief overview of the DefStan 23-009 GVA approach, describing in further detail the goals of the GVA approach. With further discussion of the relevant technical requirements when complying with DefStan 23-009 in the sub-system design process.

2.3.1 Def Stan 23-009 GVA Part 0 - Approach

Figure 2.2 below describes succinctly the ethos of the GVA approach and how DefStan 23-009 is formed, based on open standards with high level goals of creating interoperability between diverse land platform integrators and mission system designers.

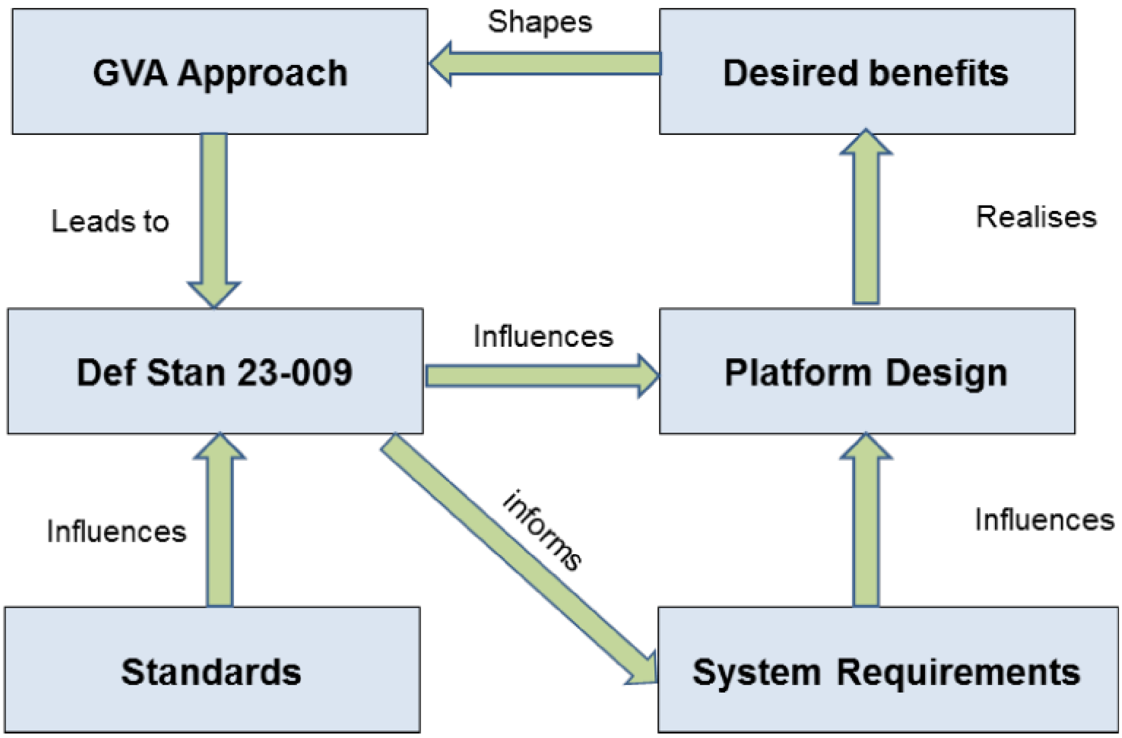

Figure 2.2 Def Stan 23-009 context [19]

The design of Def Stan 23-009 is a constantly evolving process, iteratively enhanced as new standards and protocols become available. The GVA is part of the Land Open Systems Architecture (LOSA) domain which encompasses a generic approach to all components of the land domain (i.e. dis-mounted soldiers, base of operations). LOSA is discussed in more detail within section 2.4.1 along with the LDM (defined data model) within section 2.4.2.

2.3.2 Def Stan 23-009 Part 1 – Infrastructure

The architecture view presented below Figure 2.3 describes the high-level implementation of the GVA architectural approach. Interfaces are provided for power and data to support a common approach for infrastructure compatibility. Through the use of an open data model (GVA Data Model), interoperability is ensured between sub-systems when the data model is implemented and compliance with the Def Stan 23-009 is achieved during the design phase.

The benefits of this approach provide easier upgrade paths by allowing sub-systems to communicate through a common data structure and provide the ability for vehicles to be re-roles to meet Urgent Operational requirements (UORs). It is mandated that the data model utilise the Object Management Group (OMG) Data Distribution Service (DDS) following the publish, subscribe paradigm, this is presented in further detail within section 2.4.3. Further, the (DDSI) wire protocol ensures interoperability between middleware's and therefore various sub-systems vendors. As discussed within the previous section the design process behind these developments of open standards is to promote innovation, enable interoperability between sub-systems and reduce costs throughout a platform's lifetime.

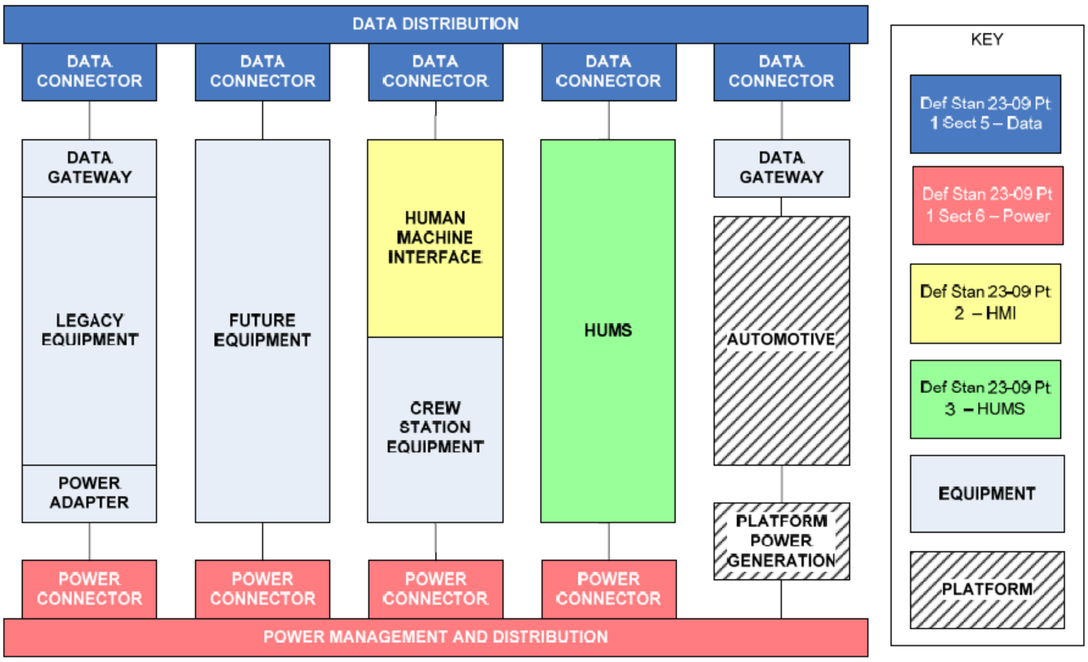

Figure 2.3 Def Stan 23-009 architectural view [26]

2.3.3 GVA Data Model and the Model Driven Approach

The model driven approach (MDA) [27] has been adopted by the Generic Vehicle Architecture data modelling group, who are responsible for the maintenance and development of the UK's GVA data model, which forms part of the Land Data Models (LDM) (discussed in more detail within section 2.4). in cooperation with manufacturers, integrators, and suppliers of military vetronic systems for military land platforms. Primarily the MDA methodology (shown in Figure 2.4) when applied to the development of the GVA Data Model provides abstraction of technology specific implementation details supporting models of military land platforms data centric electronic architecture throughout the life span of any given land platform [28]. DDS and the publish subscribe paradigm is simply the current middleware of choice for Def Stan 23-009 and is now mandated. The Platform independent modules (PIM) and Platform Specific modules (PSM) enable this flexibility of choice through a translator that translates the current LDM PIM into the desired PSM.

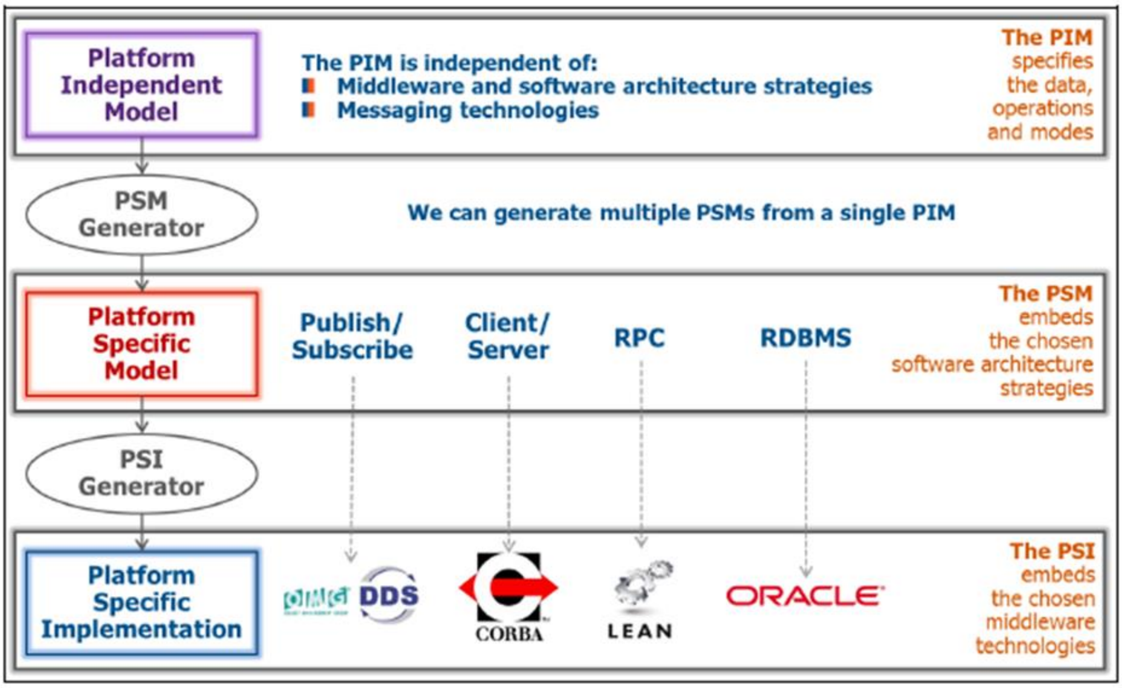

Figure 2.4 MDA process diagram

The current DefStan 23-009 GVA LDM is version 6.1 since version 4.1 released in April 2014 the model driven approach has been adopted to break the Land Data Model (LDM) into a modular DDS domain-based approach. The current released version of the GVA data model (version 6.1) provides a glance at the future structure for sensor data fusion within GVA compliant land platforms.

2.3.4 Data Management and Security within DefStan 23-009 Part 1: Infrastructure

The current DefStan 23-009 Generic Vehicle Architecture Part 1 – Infrastructure mandates the use of the OMG DDS which is an open international data-centric standard utilising the publisher, subscriber paradigm to facilitate communication between heterogeneous network nodes. This middle-ware communications platform is currently used throughout DefStan 23-009 GVA as the primary data distribution service between sub-systems, utilising the common data model described above to support complex integration by providing generic interfaces between sub-systems that could be manufactured by multiple suppliers.

There are no mandated requirements for two key components for providing support for the integration of COTS sensing technologies within the GVA environment, these are a) data security and b) data rate (i.e. how many messages per second to send of any given data). Presented below is a direct reference of section 3.15 of the Defence Standard 23-009 Part 0 Issue 4, regarding security:

“*3.15 System Security*

3.15.1 Def Stan 23-009 does not prescribe a complete network or data security solution, but it needs to be realised that adequate security assurance of operation needs to be addressed from the outset. A GVA based data infrastructure is considered an information system for the purposes of security evaluation and accreditation. Currently there is no generic approach to achieving multi-level secure functionality on a single GVA (DDS based) network architecture. Although it is recognised that SECRET and OFFICIAL operation will be required to support the range of platform functions and services, and that separate physical network infrastructure will be required to maintain adequate separation.” [19]

The emphasis for the security of any vetronics system integrated within military land platforms is given to the systems integrator to decide upon adequate security solutions for any given function taken from the SRD. Table 2.1 (following page) shows the requirements group “*Messaging*” from the current Def Stan 23-009 GVA Part 1 – Infrastructure [26]. Here GVA_INF_90 describes the requirement for the use of the GVA LDM, with GVA_INF_53 specifying the use of OMG DDS v1.2 and DDS Interoperability Wire Protocol Specification v2.1. Finally, GVA_INF_54 and GVA_INF_55 specify the DDSI wire protocol configuration specification to be used and that all data distribution must use the GVA LDM respectively. These four requirements provide the key requirements for data distribution between subsystems within a Def Stan 23-009 GVA compliant land system.

Table 2.1 Def Stan 23-009 Part 1 Issue 3 requirements group - Messaging [20]

ID	Priority	Requirement Text
GVA_INF_52	N/A	**Messaging**
GVA_INF_90	Key	All [sub-systems] shall use the [GVA Data Infrastructure] and messaging protocols for data distribution
GVA_INF_53	Key	The interface messaging protocol standards used on a [GVA Data Infrastructure] shall be the OMG Data Distribution Service (DDS) v1.2 and DDS Interoperability Wire Protocol Specification v2.1
GVA_INF_54	Key	DDSI configuration shall be as defined by Section 9.6.1 of OMG Document Number formal/2009-01-05 'The Real-time Publish-Subscribe Wire Protocol DDSI Wire Protocol Specification'
GVA_INF_55	Key	The distribution of data on the [GVA Data Infrastructure] shall conform to the GVA Data Model

The current Def Stan 23-009 doesn't provide any specific details on managing security for data transport / network, however, during the course of this research OMG DDS secure V1.0 has been released and ratified. This is explored in detail within Chapter 6, section 6.7, it is suggested from the outcome of this research that security be applied to each DM module with a tiered system, that is for example COTS sensor interface modules be highest as these as the most vulnerable with security requirements lessened the deeper into the sensor fusion framework the data travels.

2.4 Related work

DDS is a core component of the UK MOD (GVA) and NATO (NGVA) nations as it provides the abstraction required for the distribution of data within the increasingly complex electronic sub-systems found within military land systems. However, the design approach of the LOSA technical architecture (described in further detail below) requires that all data models are middleware agnostic, as such, it is required that any technical architecture design (i.e. a sensor fusion architecture for GVA) within the LOSA family of defence standards, be decoupled from the middleware layer.

Finally, the application of the generic approach is also beginning to be applied to soldier equipment (i.e. dismounted infantry) and base of operations design. This highlights the UK MoD expectations for the future battlefield, enabling enhanced connectivity between vehicle, soldier and base of operations.

2.4.1 Land Open Systems Architecture (LOSA)

LOSA is the UK MoDs overarching approach for the integration of all land systems (soldier, base and land vehicles) to realise the core benefits of the open architecture design approach (interoperability, maximum cost efficiency through life and efficient integration of equipment and services to support a brigade). [19] [29]

Designed to develop and maintain common public interfaces between all land systems with the aim of gaining all the benefits described within this chapter for through life cost savings, interoperability and provide operational agility to any deployed force now and in the future.

As such, Figure 2.5 below describes the context for how all the land domains 'fit' together to create the common Land Data model (LDM). Whilst this body of work is focused on the GVA sub-system integration with commercial sensing technologies, all land systems are considered. As it is feasible to infer that a generic approach to sensor fusion would create tangible benefits to situational awareness outside of the vehicle by allowing the dissemination of data throughout the land domain (for example, to dismounts or information being downloaded when a vehicle returns to base for further analysis, which could then be uploaded to other vehicles before deployment of recent changes to environment). This effect is described in more detail throughout the body work.

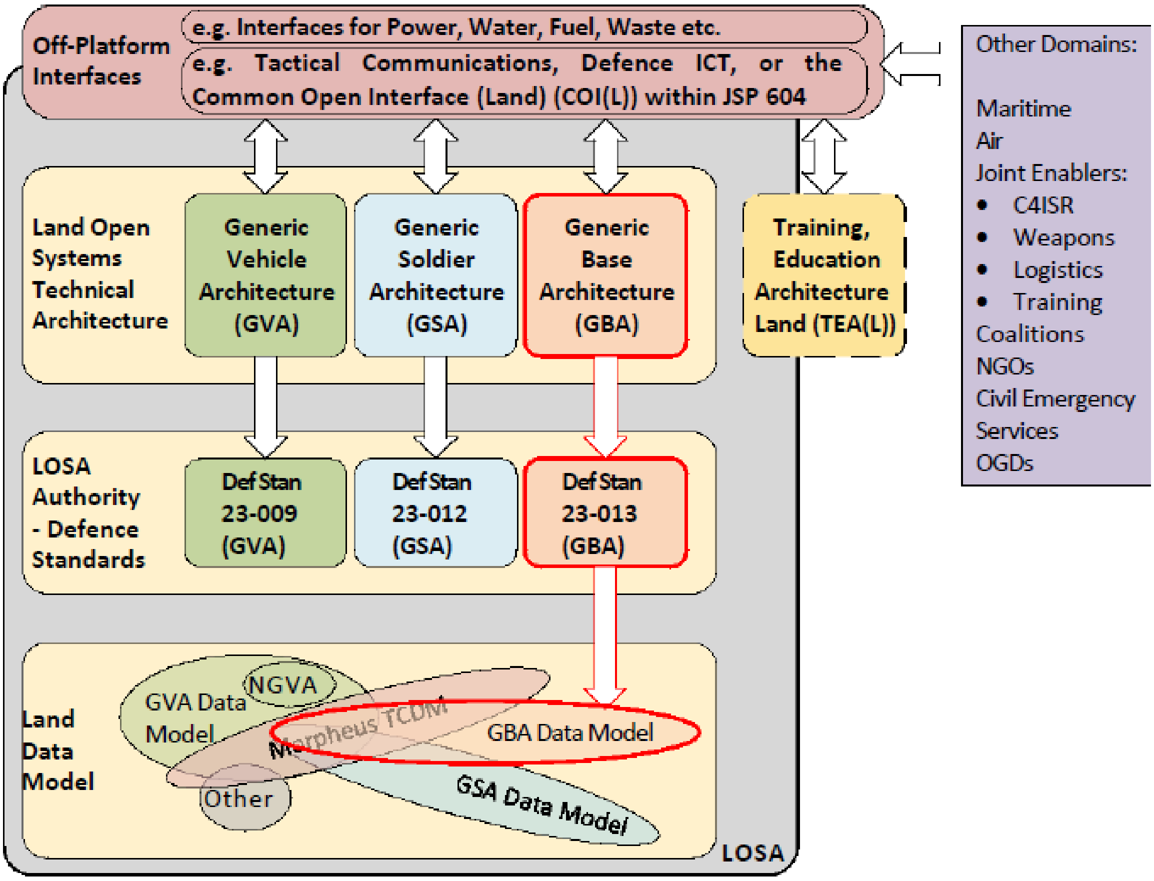

Figure 2.5 LOSA Context Diagram [30]

The following sections will briefly cover relevant aspects of the LOSA Def Stan family informing the research of the relevance of a generic approach to sensor fusion for the land domain. Moving towards an interoperable sensor fusion architecture for land systems enabling the future Battlefield Management Systems (BMS) supporting the Internet of Battlefield Things (IOBT) as discussed within Chapter 4, section 4.1.1.

Generic Soldier Architecture (GSA)

Following the approach described within LOSA the Generic Soldier Architecture (GSA) is an attempt to standardise the dismounted soldier's tactical wearable systems that form part of a soldier's equipment. The GSA approach was originally initiated to reduce the cognitive load and burden on a company group from the wearable power and equipment used by today's modern soldier.

For example, having a common power source utilising standard power interfaces allowing multiple pieces of equipment to be powered from the same source. Thus, reducing the cognitive burden on the soldier by not having them keep track of various batteries for a range of equipment, this in turn reduces the physical burden of the soldier by streamlining the power sources required to power equipment.

Additionally, the GSA approach provides all the benefits of the open systems architecture approach discussed throughout this chapter. [31]

Figure 2.6 below clearly describes the relationship between the soldier's wearable equipment and military close combat systems, military bases and the company group. It is reasonable to assume that future Battlefield Management Systems (BMS) would benefit greatly from enhanced sharing of data between these entities, this is discussed further in Chapter 4.

Figure 2.6 GSA Scope [32]

Figure 2.7 below is provided to give an overview of the GSA architecture and Integrated Soldier System (ISS), before moving on to further detailed discussions. Clearly shown is the structure of the various parts of a soldier's equipment comprised of the helmet systems, the torso systems and the weapon systems. Data and power interfaces have been defined and structured in such a way as to allow two-way transfer across the entire architecture.

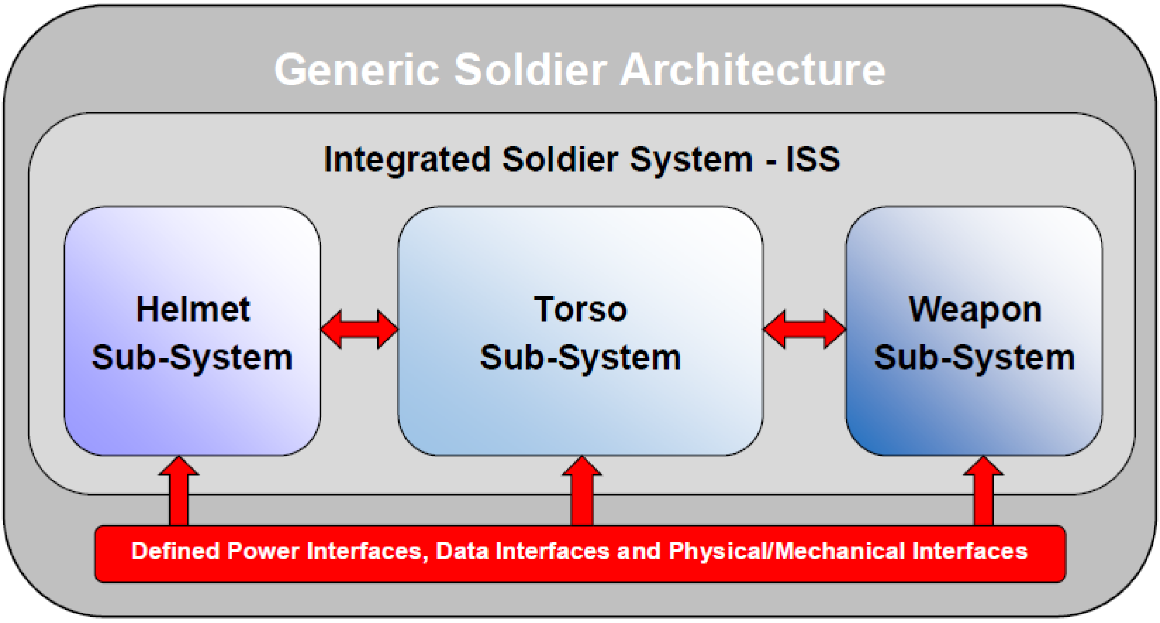

Figure 2.7 GSA Logical Architecture Breakdown [32]

Figure 2.8 describes in greater detail an example of an ISS architecture within the GSA. Here we can see the logical breakdown of the Helmet, Torso (body) and weapon sub-systems.

Within the helmet sub-system, we can see the optional equipment components such as current role equipment (night vision, tactical zoom lenses etc.) and any optional processing units. The common power source is also described, linked to all sub-systems and to the torso power source. Finally, the data links can be seen providing data transfer between sub-systems and also to the torso processing unit.

The torso provides the architecture's main power source connected to the helmet sub-system and the weapon sub-system whilst also powering the torso equipment. Common data links again are described linking the communications equipment, role specific equipment and the processing / HMI equipment. Of note is the external, off dismount interface (gateway) allowing data transfer from the dismount equipment to a vehicle or to the base of operations. The data provided by this gateway could be critical to the overall force situational awareness when fused with data on board a vehicle, for example.

Finally, the last module of the ISS architecture describes the weapons sub-system, consisting of the weapons platform itself with a data link to optional processing unit / HMI and any tactical weapon attachments which also has common data links to the optional processing module. The optional processing / HMI again has a common data link back to the torso sub-system allowing the transfer of data off dismount via the torso interface back to a base or vehicle.

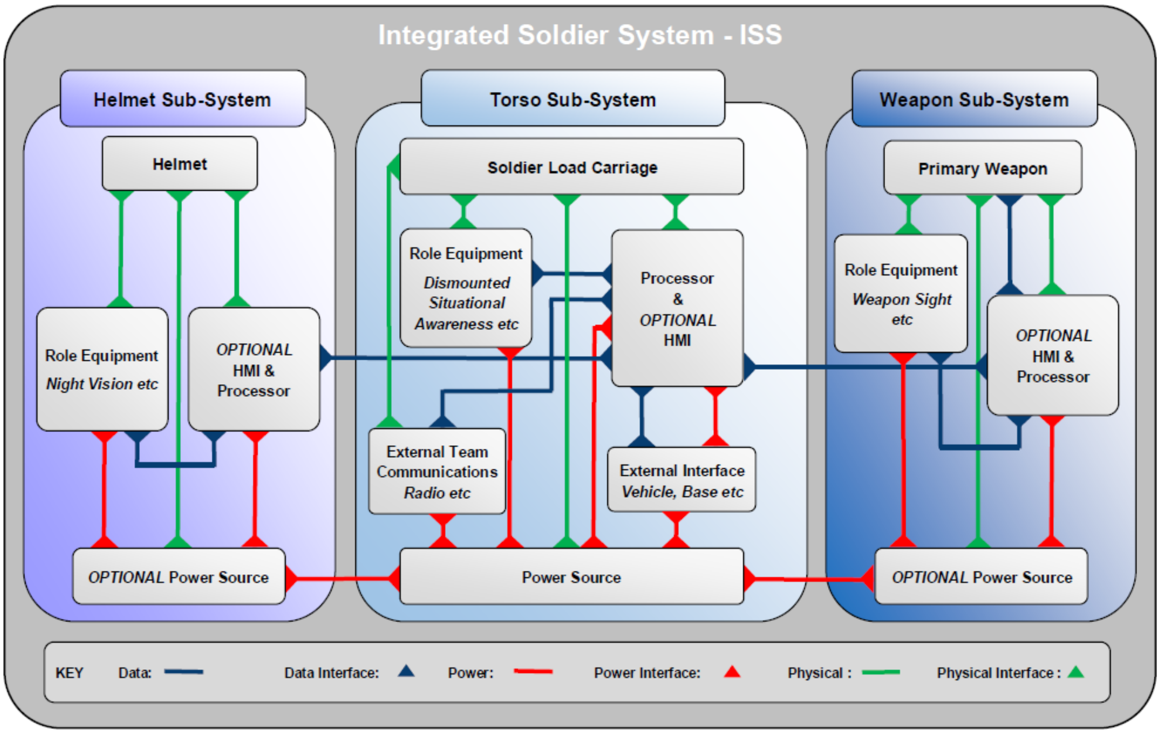

Figure 2.8 ISS Example Logical Architecture [32]

What is of particular interest to this research are the common data connections and the optional HMI / processing components between each sub-system which are then linked to the torso external, off platform dismounted interface (gateway), providing data transfer to a base or vehicle. These architectural decisions could feasibly allow the potential for advanced situational awareness of a company or force group by fusing the data from multiple dismounts with the data of the vehicle sensing technologies itself providing an enhanced local situational awareness for the crew and the dismounts. This is described in more detail within the conclusion of this chapter (section 2.5).

Generic Base Architecture (GBA)

Naturally the GBA follows the ethos described within the LOSA family of defence standards (Def Stan 23-012, Def Stan 23-013 and Def Stan 23-009), for openness, modularity and availability adopting this approach the UK MoD aims to standardise the interfaces and protocols used within a base of operations to effectively support Facilities Management

(FM). FM is a critical component of the GBA providing the effective implementation of all services to and from the base of operations such as power, water, waste and data management. [30]

Figure 2.9 shows the boundaries of the GBA in relation to platform systems. Clearly shown in green is the GBA with all other platform systems in white.

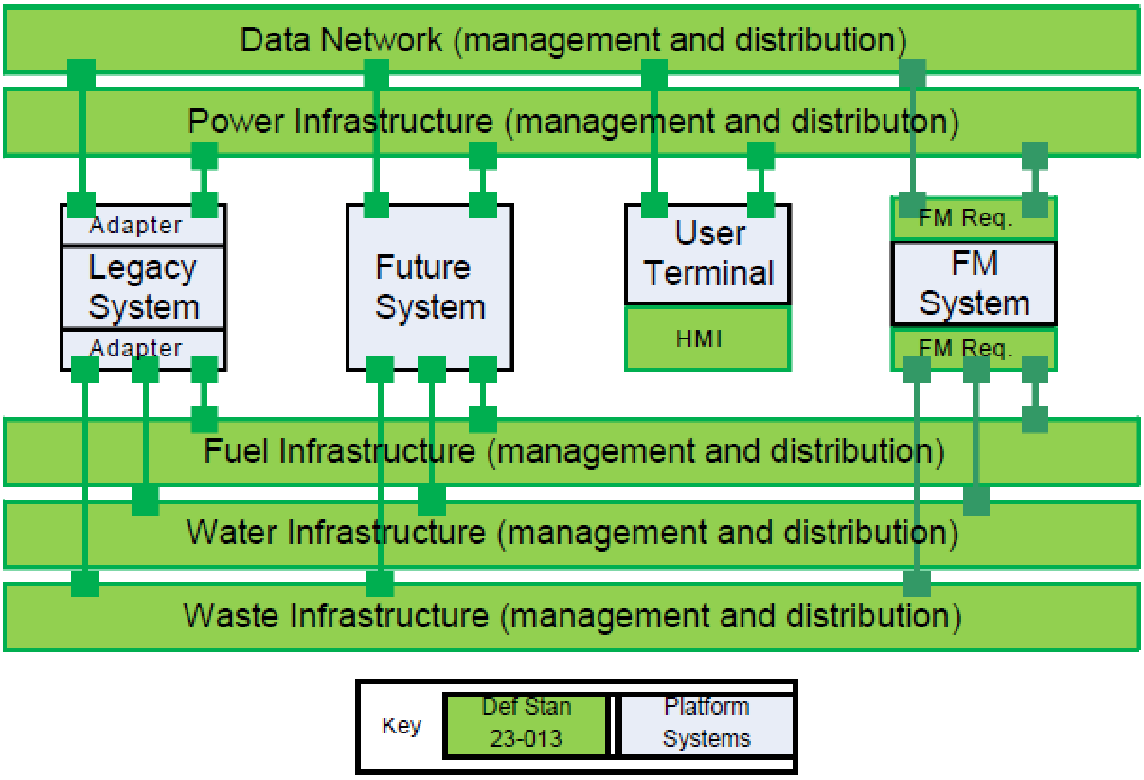

Figure 2.9 GBA Boundaries [30]

Within Figure 2.10 the anticipated future data interfaces for a GBA architecture that interfaces with the GSA and the GVA are presented. Shown are the waste, power, fuel and data interfaces between the GBA (Def Stan 23-013) and the GSA (Def Stan 23-012), GVA (Def Stan 23-009). A gateway is also described providing the external link outside the LOSA domain. The data interfaces are of interest to this body of work given the use cases developed in conjunction with the UK MoD presented in chapter 5. It is conceivable to assume that these defined, common public data interfaces could be used by a generic sensor fusion architecture to use the base of operations as a data warehouse capable of fusing larger amounts of daily data provided / downloaded from the dismounts ISS and the MCS. This concept will be discussed in further detail within the conclusion of this chapter.

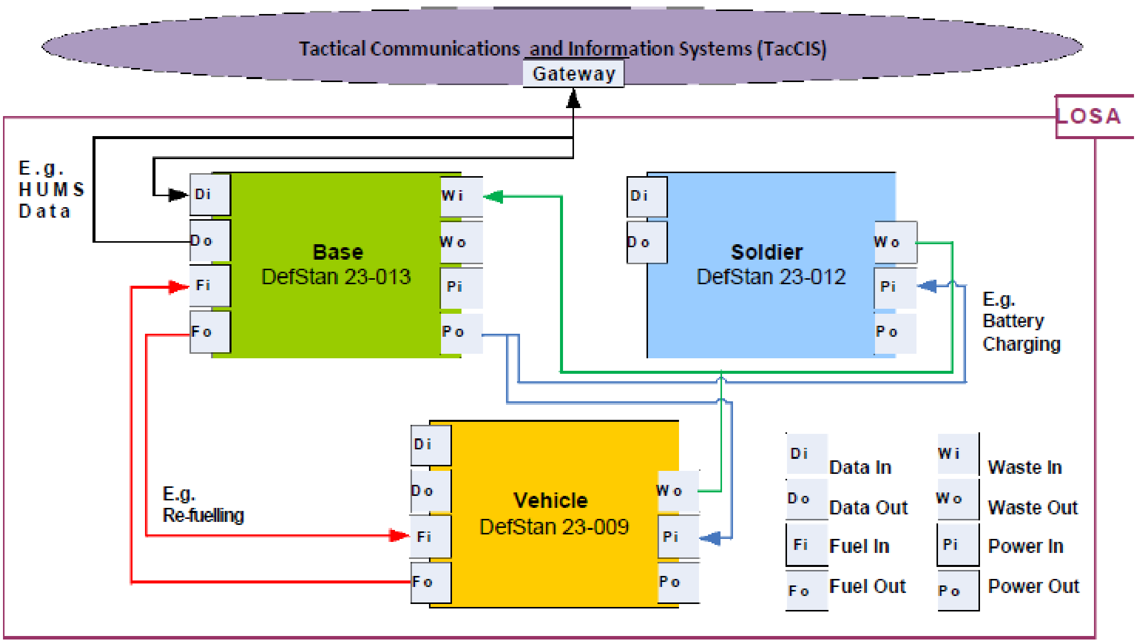

Figure 2.10 Anticipated Future Interfaces between the Base Architecture and Vehicle & Soldier Architectures, as well as externally [30]

2.4.2 Land Data Model (LDM)

The LDM is described as an interface software development kit and is owned and maintained by the UK MoD, Defence Equipment and Support, GVA Office. It is based on the OMGs Model Driven Architecture approach described earlier within 2.3.3 GVA Data Model and the Model Driven Approach, page, 37. The LDM provides a complete tool set for developing, maintaining and implementing all the Def Stans contained within, it also encompasses the rules, processes and ethos for the development of the land defence family of standards. [33]

2.4.3 Data Distribution Service

Whilst this section will provide a brief overview of the DDS specification, greater detail will be entered into where appropriate throughout the following chapters of this thesis. DDS is an open standards middleware software designed to facilitate the network or shared memory distribution of data between multiple network nodes independently from platform architecture or programming language. DDS implements a data centric, publish-subscribe paradigm, utilising common interfaces through an agreed data model / structure to allow the various network nodes to communicate with each other regardless of their platform specific architecture (Figure 2.11 describes this abstraction). Originally ratified in 2002 (released 2004) by the Object Management Group (OMG) standardisation consortium having been created by a partnership between United States (US) defence contractors, Thales (France) and Real Time Innovations (RTI) [34]. It has since been adopted throughout various commercial, industrial and defence sectors for various applications, the current standard specification is now version 1.4 released in 2015 [35].

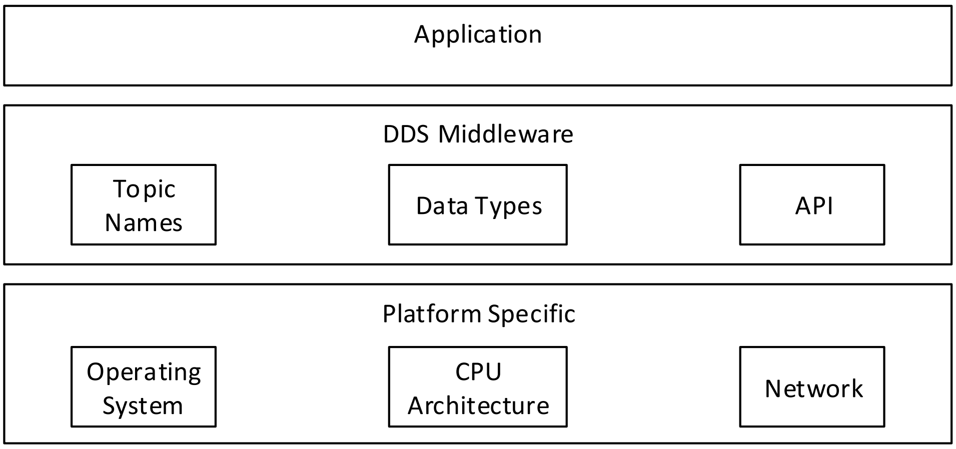

Figure 2.11 Data Distribution Service middleware abstraction, adapted from [36]

At the heart of DDS is the data model, typically designed in Unified Modelling Language (UML) and parsed into Interface Definition Language (IDL) files, it describes all data to be exchanged between nodes for any given application. The entire systems data exchange is typically modelled first, then the derived IDL file(s) are created which are compiled into the API programming language and platform architecture of your choice (i.e. Java, C, Ada, C++, for x86, ARM, Linux and so on).

Data centricity is a core attribute for DDS, rather than developing applications to send and receive data, applications in DDS are written describing how and when to share data. Semantic topic names are chosen and used to describe the data being published, once available the middleware maintains a local store within each node (joined to any given domain) of all nodes currently discovered, their data type, topic name and Quality of Service (QoS) configuration. Consumers of data can then subscribe to any data they wish as often or as little as required and publishers, subscriber can also join and leave domains in an ad-hoc manner.

Given that the purpose of the GVA is to support a generic and modular approach to land systems design (due to the long-life cycles of these platforms), the functionality offered by DDS aligns with the GVA in many ways. Supporting a complex digital system with independent interfaces that once implemented can integrate cost effectively.

Figure 2.12 presents an overview of the DDS core concepts and operational structure, it shows how multiple publisher applications written in different programming languages potentially running on different processing architectures, can provide data to any interested subscribers. Publishers or subscribers can join or leave a domain at any time.

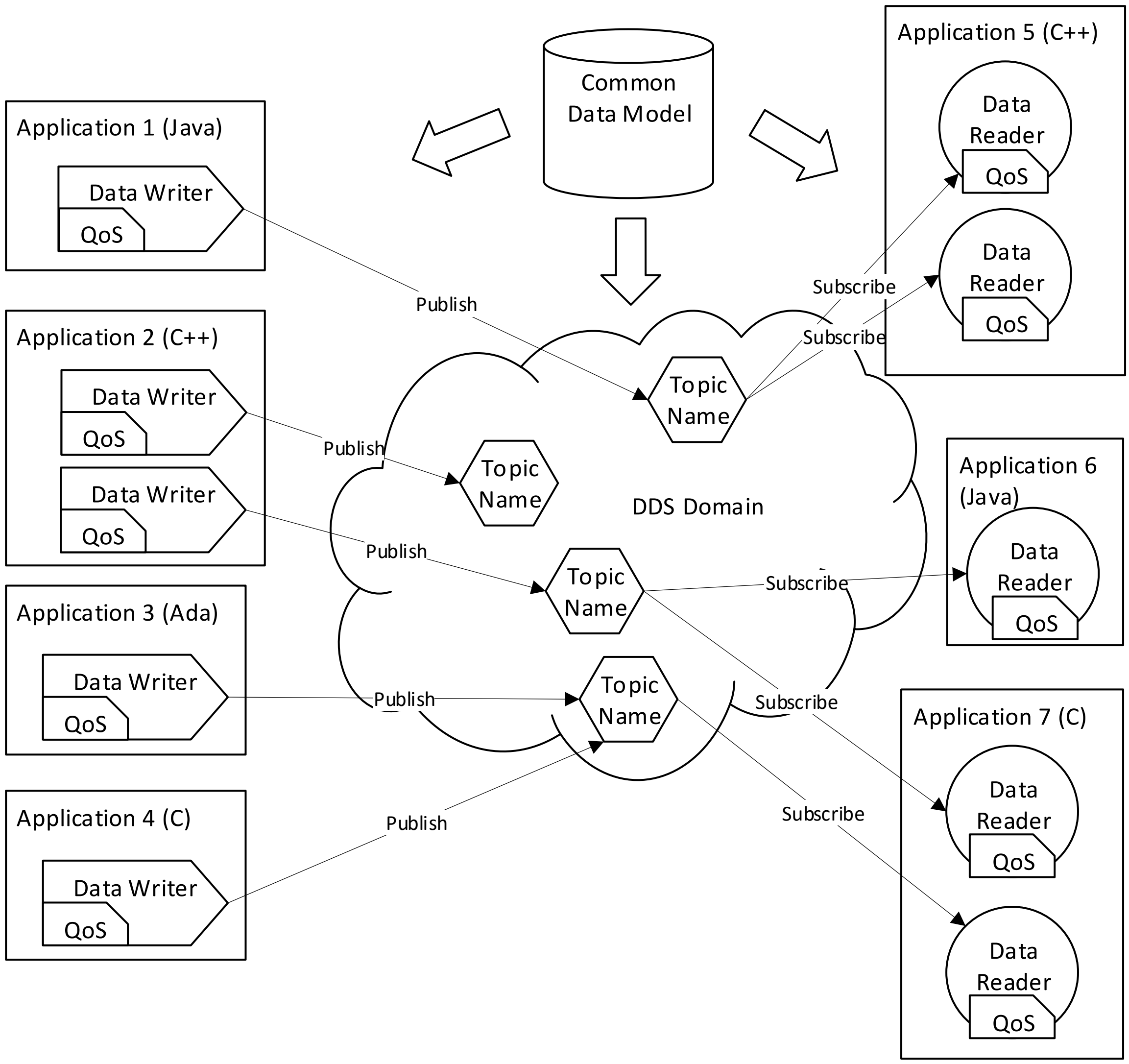

Figure 2.12 DDS publish subscribe pattern, adapted from [36]

OMGs DDS specification is currently the selected middleware technology. Aligning with the ethos of the LOSA approach, GVA is designed and developed in such a way to allow the use of multiple middleware technologies to facilitate data transfer between nodes. This supports openness and modularity. However, DDS is currently the middleware of choice for the STANGA 4754 NGVA and the Def Stan 23-009 GVA.

2.5 Conclusion

This chapter provided an overview of relevant components of the UK MoD Defence Standard 23-009 Generic Vehicle Architecture. The chapter described vetronics, vetronic integration approaches and open systems standards, highlighting the thought processes behind these standards and why they have been selected by UK MoD. A discussion was also presented regarding the mandated data distribution middleware technologies and the design process behind these technologies, the importance of the data centric approach, providing an introduction to the OMGs DDS standard (currently the middleware of choice for the UK MoD). Finally, a brief overview of the peripheral (to this body of work) LOSA family of standards was presented which included the Def Stan 23-012 GSA and Def Stan 23-013 GBA along with the LDM. The results of this review provided critical insight to highlight the constraints of as well as the potential opportunities when harmonising COTS technologies within the Def Stan 23-009 GVA environment.

The current direction for the GVA approach to land systems design is influenced not only by new technologies and research, such as, the current body of work being presented here but also by the LOSA family of standards, Def Stan 23-012 GSA, Def Stan 23-013 GBA. As a natural course for the evolution of the Def Stan 23-009 GVA and with the growth of cost effective, smarter technologies, all land assets are becoming increasingly connected to each other which provides opportunities for enhanced situational awareness, operational planning and meeting UORs.

As discussed, the purpose behind keeping the technologies used within LOSA open and modular allows the LOSA family of standards to remain flexible and cost effective. If a new or current, open, middleware standard offered an advantage over the selected middleware technology (currently DDS) the LDM can be immediately translated to utilise these middleware technologies. However, in practice obviously modifying the entire land systems vehicle inventory (for example) to utilise a new middleware technology would likely be unfeasible due to technological, logistical and cost constraints. Future platforms could however begin to realise the benefits of the new middleware technology.

Given the original hypotheses of the work and whilst completing the original research proposal it was immediately clear that sensor fusion was a critical, architectural component for modern autonomous vehicles utilising combined sensing technologies. Whilst there are currently no sensor fusion capabilities modelled within Def Stan 23-009 GVA, it is anticipated that during the course of this research that will of course change[1]. The following chapter presents the literature review for sensor fusion frameworks / architectures, sensor fusion architecture topology and relevant automotive bus protocols. Additionally, the next chapter also presents the related work to this thesis.

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[1] During the course of this research, the research outputs prompted the UK MoD to begin to model sensor fusion within the GVA data model, as seen in DSTL/AGR/00723/01.290416.WP3.D. [37] S. Murphy, "Confidential Deliverable Report; DSTL/AGR/00723/01.290416.WP3.D1," Vetronics Research Centre, Brighton, United Kingdom, , 2016.

3 Sensor Fusion Architectures and Networks

3.1 Introduction

Given that an intelligent transport system or at least, semi (level 3) and fully (level 4-5) autonomous individual commercial automotive solutions are predicted to be available by 2020 as described by various governments and academia [38-41], the challenges that have been overcome and that still have to be met, are and have been, enormous.

Tummala et al. [42] shows that the recent emergence of advanced automotive sensing technologies being researched, improved and produced cost effectively, has risen dramatically in recent years. These new sensing technologies are being implemented utilising current sensor fusion architectures to provide vehicles with an exceptionally reduced error rate with regard to the sensor information being provided, essentially providing the vehicle with advanced situational awareness of their environment.

However, that being said there are many problems associated with these current technological solutions. Specifically, research points to the problem of the integration between many advanced sensing technologies that provide an automotive land platform the ability to have an awareness of its surroundings [43] [44]. This awareness supports the vehicles ability to plan trajectories, manoeuvres (lane changing etc.) and operate safely within chaotic, complex environments as described by Golstan et al. [45].

Given that this is the case this research intends to follow the premise that if a machine can utilise these technologies to provide advanced situational awareness to its trajectory planning systems, then we can also use a similar approach to provide the crew of the MCS with advanced situational awareness. This application of research will support the system's ability to sustain the crew and greatly add to their survivability within the urban environment. Added to this is the fact that the system will also greatly enhance the safety of any civilians within the MCS's local environment.

Currently many models exist and have existed for many years, utilising multiple sensory data and fusing them together to provide enhanced environmental awareness and informational precision to aid decision making [46-48]. Unfortunately, the current fusion process must be designed for the system it is required and fine-tuned to meet the requirements of the system, this is both costly and time consuming but more importantly prevents scalability or support for system changes, A. Knoll et al. propose a partial solution to this problem here [43, 49] by presenting a semi modular approach to the design of the sensor fusion architecture. Although their design predominantly focused on the single task of autonomous parking to demonstrate their approach and only specific parts of their algorithm have the ability to be modular in design along with using a centralised architectural approach (the constraints of this approach are discussed within section 3.2 Review of Sensor Fusion Architectures).

As adequately put by Elmenreich "*For the future it would be advantageous to elaborate ways that provide inter-operation between components of existing fusion architectures instead of creating even more isolated systems anew*."[46]. This research will address these issues during the course of development documenting and implementing a generic modular approach. The research will, during the development and design of the final solution, try to answer how the architecture can be designed as modular as possible.

3.2 Review of Sensor Fusion Architectures

This section presents a selection of the current sensor fusion architectures available, paying particular attention to the architectures that provide support for automotive applications. Whilst this is the case, the research scope shall not be constrained to these designs or approaches. A description of the beneficial characteristics and constraints of each architecture for the purpose of comparison.

In general, it could be said that sensor fusion is literally as it sounds; the fusion of multiple sensor data being combined to increase the verification of a detectable event occurring. In other words, the sum of the system far exceeds its individual parts [47, 50].

Whilst the following models reside at the highest level of abstraction, they describe not only the underpinning understanding of the system processes but also the information/data flow throughout the system. This therefore affects the performance of the system and the implementation and maintenance lifecycle processes, which in turn affects costs and deployment viability.

All of the conceptual or functional models reviewed have no intrinsic consideration for safety critical design processes (deterministic communication and fault tolerance etc.).

3.2.1 The Classical JDL Fusion Architecture

Developed during 1985 under supervision from the US. Department of Defence by the US. Joint Directors of Laboratories [51], the primary goal of the research was to provide theorists, computer scientists, engineers, etc. with a model that promoted the clear and more importantly a common understanding of data fusion techniques [52].

As shown within Figure 3.1, the JDL model consists of five levels of data manipulation and processing coupled with a data store. The physical transport layer configuration provides a bus topology, connecting all high-level processing modules within the architecture.

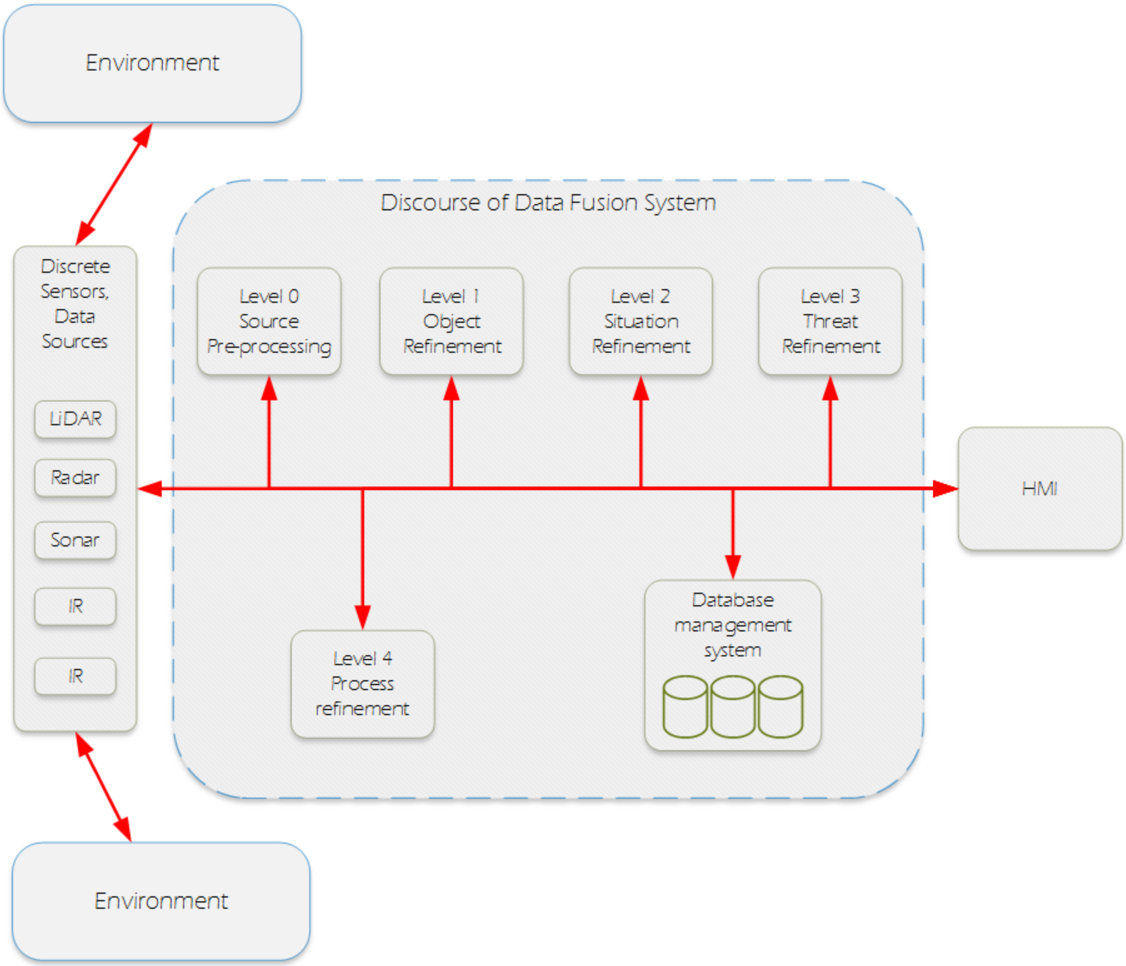

Figure 3.1 US Joint Directors of Laboratories model (JDL), adapted from

The following presents the abstract behaviour of each module shown above.

Discrete Sensors, Data Sources – This level provides the system with raw data from various sources such as, sensors, a priori information, data stores and human centric data sources (wearable devices etc.).

(Level 0) Source pre-processing – Pre-detection and processing. System design dependant, this level can be used to reduce load on the fusion processes by pre-screening, signal processing etc.

(Level 1) Single object refinement: *(fusion can occur here)* – Here we are concerned with the estimation of specific object parameters, such as current velocity, current trajectory and possible predicted future object states. Identification can occur here also, using classification methods (CBR (Case Based Reasoning) etc.).

(Level 2) Situation refinement: ***(fusion occurs here)*** – Within this level, we provide the system with context by examining the relationship between objects and observed events, the purpose of which is to create meta-objects that give the system an estimated interpretation of the current situation. Aggregation of objects can occur here.

(Level 3) Threat / implication refinement: ***(fusion occurs here)*** **–** Processing here supports the system ability to predict possible events, outcome of events if certain courses of actions are taken and predictions of future situations. This can be based on a priori knowledge and inferences can be made at this level providing information on possible future opportunities and or future vulnerabilities.

(Level 4) Process refinement – This level is a system meta-management processing stage. This is used to not only monitor system behaviour, performance (to meet system/objective/mission requirements) but can also relocate system resources, be that processing, sensor allocation, or objectives. This level can be viewed as supporting the overall system objectives, providing the system with flexibility if said system has been designed with this in mind. This is essentially the system control process. Table 3.1 presents the benefits and constraints of the JDL model.

Table 3.1 Benefits and Constraints of the JDL model

Benefits	Constraints
• Real time processing neither supported nor hindered by the model, • Concurrent processing available, • Order of processing is irrelevant, • Well documented use and approach within military applications, • The model provides a helpful common understanding of how to apply sensor fusion.	• Order of processing for specific applications may indeed be highly relevant therefore extra pre-processing overheads need to be taken into consideration when designing the system. This would need to be incorporated within the level 4 module and would add design complexity to the required application, • This original model does not support the fusion of multi-image signals, due to this type of data requiring many levels of fusion such as pixel fusion, feature level fusion, decision level fusion and multi-resolution etc. • Being a data centric model, if followed presents difficulties if the system after completion requires extensions or modifications, • The conceptual model is presented with a high level of abstraction which can make it difficult to apply the model to specific problems. That is, the model is so conceptual that an engineering team or non-system development related parties are given no idea of how to interpret the model for implementation.

Whilst helpful to a developer / system engineer to understand the overall architecture, specifics are omitted therefore the developer is not guided in the creation of a real architecture.

3.2.2 The Omnibus Model

In contrast to the slightly ambiguous JDL model, the Omnibus model provides system engineers with an elegant, more descriptive (defined) solution to management of SoS (Systems of Systems) data fusion techniques. Developed by Mark Bedworth and Jane O'Brien in 2000 [53]. The model attempts to combine aspects from different models removing some of the constraints of those approaches whilst also of course containing its own limitations.

Similar in structure to the Boyd control loop or OODA (Observe, Orientate, Decide, Act) loop developed by John Boyd [54] a U.S. Air Force pilot between 1951-1975. The Omnibus loop shown in Figure 3.2 incorporates features from the JDL model, Boyd loop and other models but attempts to remove the military flavour providing a more generic environment for the development of sensor fusion systems.

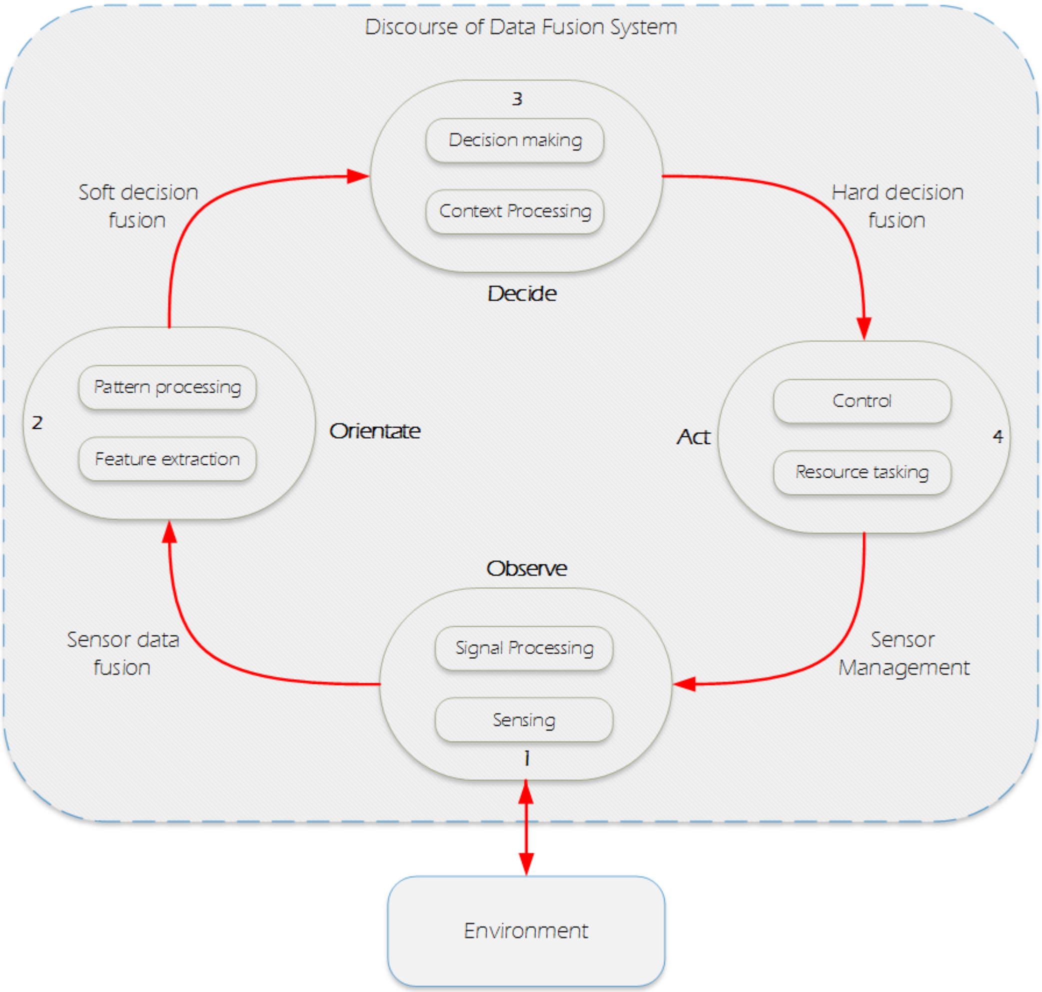

Figure 3.2 Omnibus high-level model

The nature of this structure however also again constrains aspects of deployment of this model for our purposes. The diagram presented below (please see Figure 3.3) further outlines the unique nature of the behaviour of this model by detailing the model's handling of sub-processes. It can be observed that the model in its entirety is recursive in nature, with each sub process containing the same structure as the overall conceptual model.

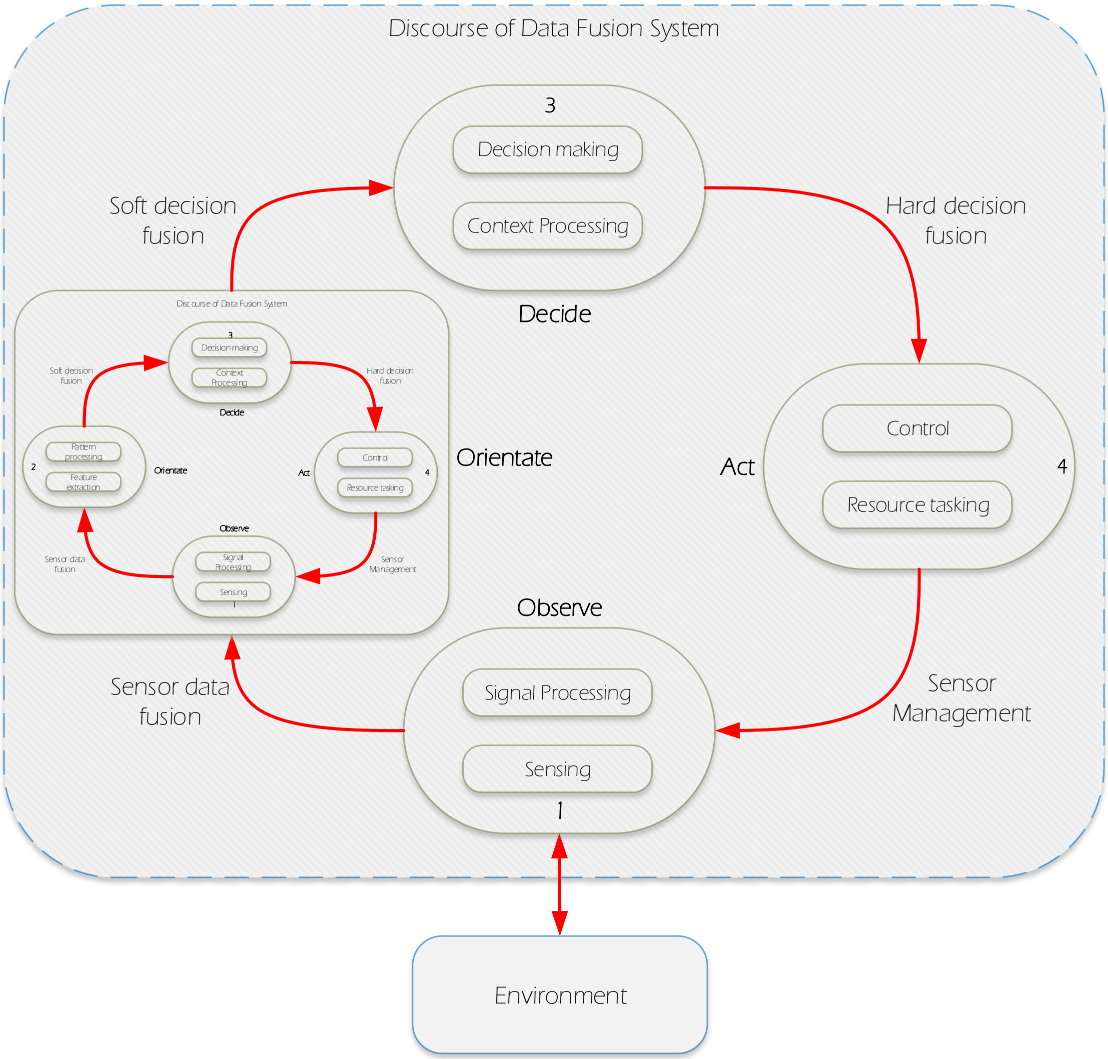

Figure 3.3 The Omnibus model - subtask processing approach

The numbered objects (1-4) are comparable to the JDL model's levels describing the behaviour of each level. However, there is no dedicated system storage depicted in the Omnibus model such as a database management system etc.

Table 3.2 presents the critical analysis of the benefits and constraints of the Omnibus model in further detail, features supported by the Omnibus model are also described here.

Table 3.2 Benefits and Constraints of the Omnibus model

Benefits	Constraints
• Whilst offering the same cyclic nature of the OODA loop the Omnibus model provides a far greater level of detail within the sensor fusion architecture design process, • The recursive behaviour of the model allows the design process to follow the same principles from beginning to end due to the structure of the sub-processes being identical in design to the overall model. Thus, allowing the system to be designed in a logical manner with the same overall modelling process, • Again, this approach is supportive of real time processing, • Whilst perhaps not of direct importance the model provides generic terminology rather than defence oriented, therefore assumptions are not made regarding the application of the system.	• Does not support concurrent processing due to the cyclic nature of the design, • Will not support a distributed sensor network due to the above constraint; however, this could possibly be mitigated with further research and adaption of the model, • The model would certainly benefit from a persistent storage medium allowing the prior knowledge derived from previous iterations to be considered by the current iteration for the hard fusion and action to take modules. Currently this is not in place within the model, • Due to the cyclic nature of the model the access to the DBMS (Database Management System) could only be achieved once per iteration of the entire model. Thus, reducing decision making capability on the fly, as it were. An action could only be taken after 1 complete cycle.

However, it should also be noted that the Omnibus model itself is more of a functional, behavioural description model rather than a description of architecture. This in turn creates the need for deeper research into implementation methodologies of this model when creating a working prototype.

3.2.3 The LAAS Architecture

The LAAS (Laboratoire d’Analyse et d’Architecture des Syst`emes) architecture was developed by Alami et al. [55] and published in 1998, the architecture was specifically designed with autonomous mobile robotic platforms in mind. This architectural approach was developed to support real time processing of local environment fused sensor information from the outset, whilst also supporting software reuse and a variety of sensing technologies. The individual levels also logically breakdown the model into a practical implementation of the system allowing the developer to design and provide the required behaviours for the system at hand.

Figure 3.4 below shows the interaction between the components of the conceptual model that forms the LAAS architecture.

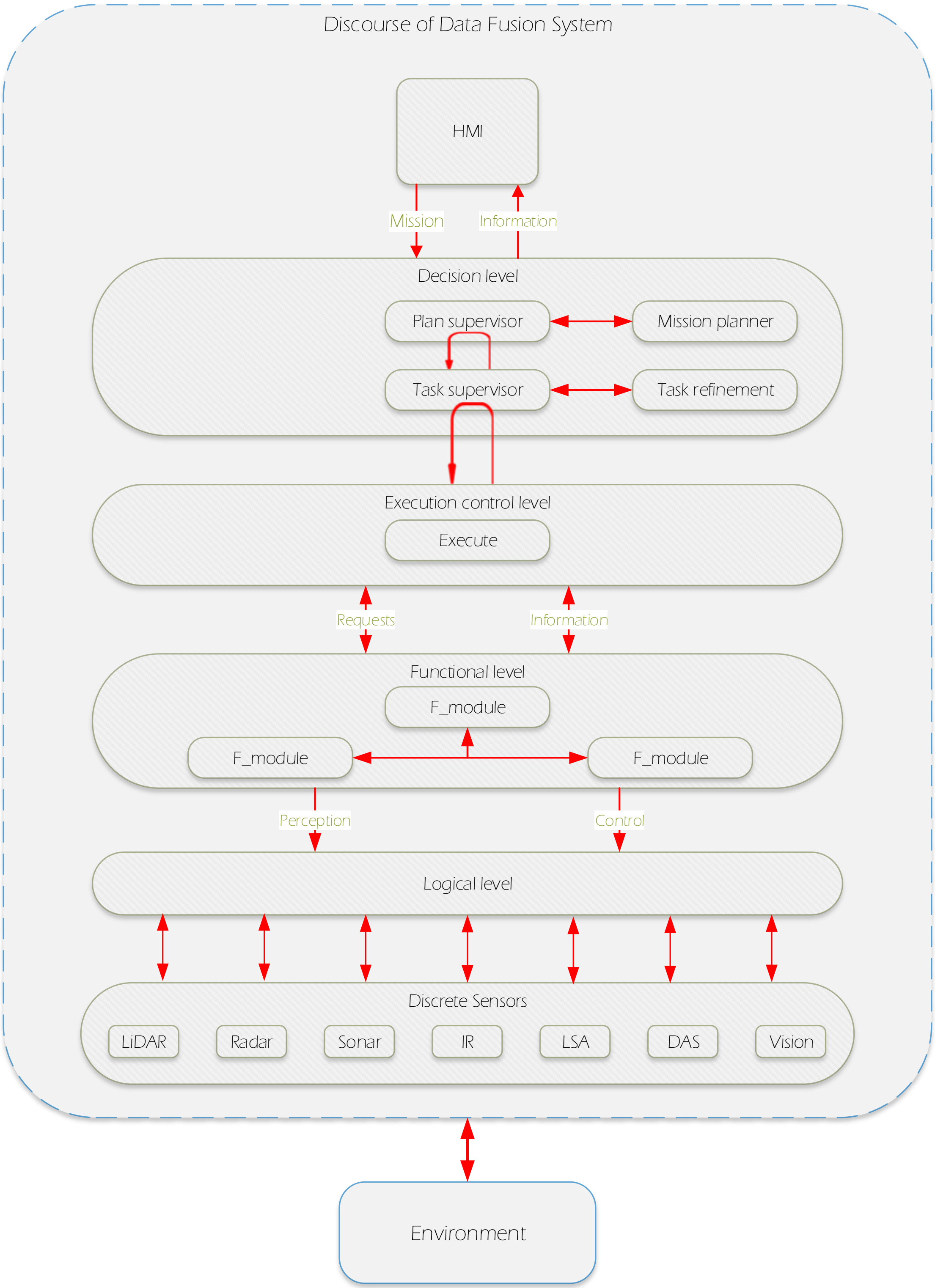

Figure 3.4 The LAAS architecture

The levels are categorised as follows:

Logical level – The purpose of this layer is to provide the interface between the physical sensors and the functional level.

Functional level – This layer consists of all the built-in functions of the robot or in our case the vehicle such as, image processing functions, control loops, automotive functions (engine control, electronic architecture reports and CAN / MilCAN controllers etc.). These would all be separate, controllable modules that are able to communicate with each other within this level.

Execution control level – This level controls and coordinates all the execution of functions within the modules under its control that have been included in the previous level, depending on the task requirements.

Decision level – Finally, the decision level provides the entire architecture with the capability of completing the task/objective currently presented to the system via the operator. The plan and execution of said task is supervised within this level, whilst also being reactive to the events generated within the execution level during the whole process. Different models of this level can exist, and the decision level can be composed of further levels within itself providing representation abstractions and temporal considerations.

The LAAS architecture provides many benefits related to the capabilities we are proposing to provide a military land platform. Table 3.3 presents the critical analysis of the LAAS architecture benefits and constraints.

Table 3.3 Benefits and Constraints of the LAAS architecture

Benefits	Constraints
• Highly reconfigurable, • Supportive of real time applications, • Modular design within each level allows for easier interoperability within existing systems, • Provides strong support for application that requires a generic approach to architecture design, • Promotes reuse of modules and lower-level code / software, created to control the system, this also allows modules that are already part of the system to be modified as and when required (such as the land platform has an upgrade, or the mission/task requires vehicle modification).	• Whilst the overall design promotes generic implementation the model itself has already made design decision for the engineer, therefore the overall flavour of the model leans to a more rigid architecture than initially seems apparent, • Due to the constraint noted above the cost of moving a system developed within this conceptual approach to another fusion architecture could prove to be very costly with an almost entire architecture redesign, • Concurrent processing is only really supported within each level rather than level independent. Depending on the task/mission objective each level would have to be processed within a specific order. However, this may be able to be overcome after having completed further research into this type of architectural structure.

3.2.4 The Revised JDL Model for Automotive Applications

The following architecture described within this final section is one of the most interesting within this investigation and arguably the most relevant to the current research. Following the model devised by the Joint Directors of Laboratories Data Fusion Subpanel (JDL DFS) as reviewed within section 3.2.1. This revised JDL model offers specific notation to allow for the inclusion and development of safety systems within an automotive context.

Polychronopoulos et al. [56] demonstrated a further refinement of the original conceptual JDL model to provide greater detail and specifics related to automotive safety applications. Developed during a European automotive research initiative named PReVENT which ran for a duration of 4 years from 2004 to 2008 and contained 50 European partners from the most prominent vehicle manufacturers and tier 1 automotive suppliers. These include but are not limited to: Volvo, Fiat Research Centre, DaimlerChrysler, DELPHI, FORWISS, IBEO, ICCS, INRIA, SAGEM, and the Chemnitz University of Technology.

A sub research project within this produced the so-called ProFusion 2 (PF2) functional model. The output of the research attempted to bridge the gap between existing sensor fusion architectures (predominantly military based) and the rapidly expanding electronic automotive safety engineering (ADAS etc.) which required sensor fusion processes. That is, the research attempted to address the question of how the JDL model could be expanded beyond the military context.

Figure 3.5 shows the highest level of the proposed model. The overall approach was to modify the existing JDL approach to architecture design and split the JDL architecture into 3 distinct hierarchical layers, these are as follows:

- Layer 1: system perception processing and fusion (JDL Level 0 and 1),
- Layer 2: system decision and application processing and fusion (JDL Levels 2 and 3),
- Layer 3: This layer contains the action to be taken or the Human Machine Interface (JDL Level 5).

These layers should be implemented completely independent of each other thereby encompassing their own physical (discrete) resources such as processing units and physical network structure. The architecture however only allows communication in one direction between the highest-level layers (layer 1 to 2, and 2 to 3).

This constraint in turn prevents the architecture from supporting real time concurrent processing of the individual highest-level layers. The reason for this approach is to prevent inconsistencies between interoperable system components and data attributes such as time delays etc. Whilst the authors acknowledge this is a trade-off between safety requirements and the benefits and flexibility of concurrent processing. Although internally the layers can perform fully concurrent real-time processing operations.

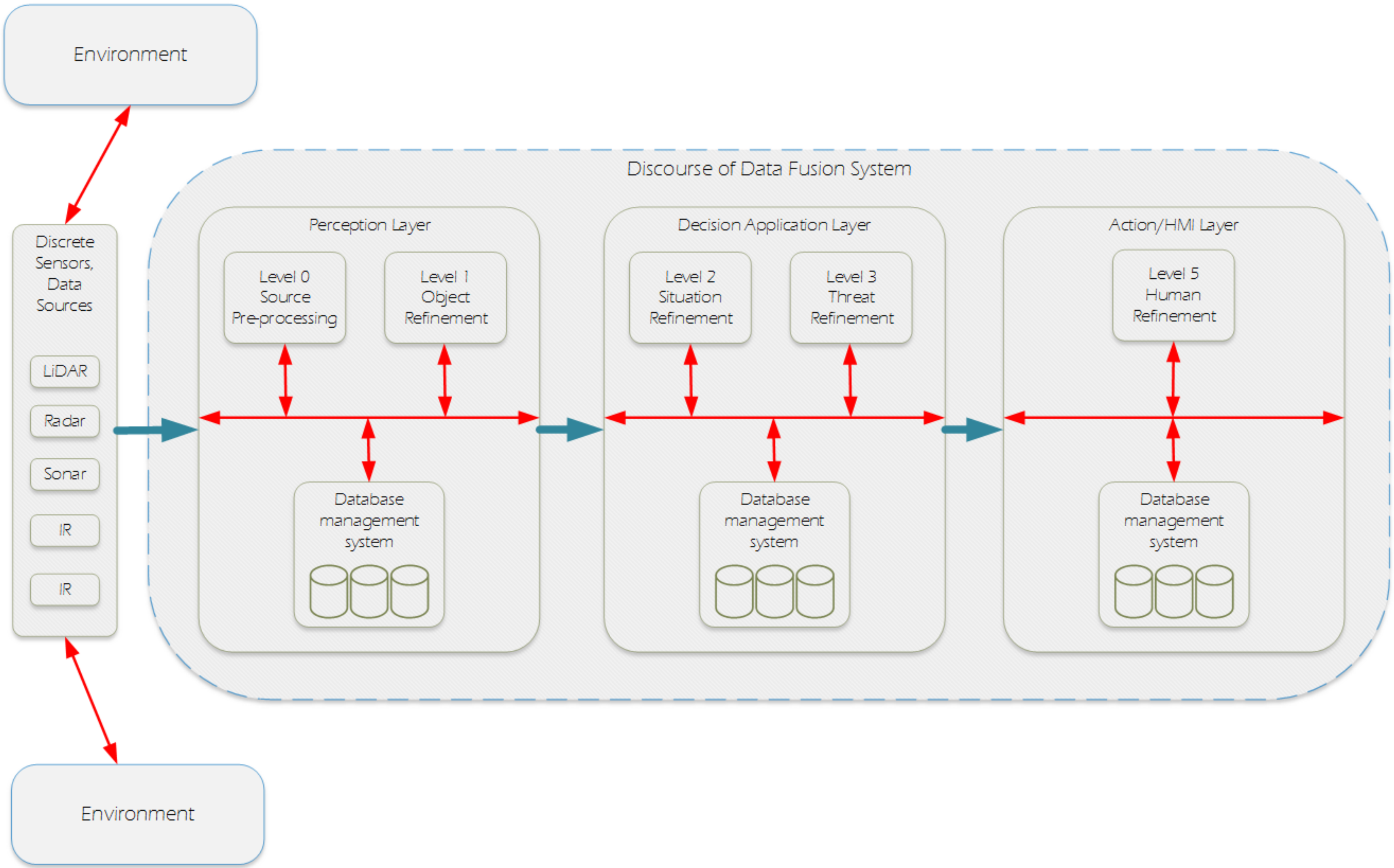

Figure 3.5 Revised JDL Model for automotive safety applications [56]

Figure 3.6 is a detailed view of the first hierarchical layer (Perception Layer) as shown in the previous diagram (Figure 3.5). It demonstrates the ability of the architecture to break up the fusion process into functional fusion blocks that provide the fusion algorithm with the ability to retrieve the best data possible for the given current task being asked of the system.

This is achieved by allowing each of the nodes presented below to be able to communicate back and forth to each other until the expert system component is satisfied that the task has been met (given the requirements of the task).

For instance, resources can be reallocated here if say a sensor became disabled due to either malfunction or physical damage. Previous data can be used, or another sensor or groups of sensors (with a fusion process) can be used to provide the system with the same capabilities that the damaged sensor offered.

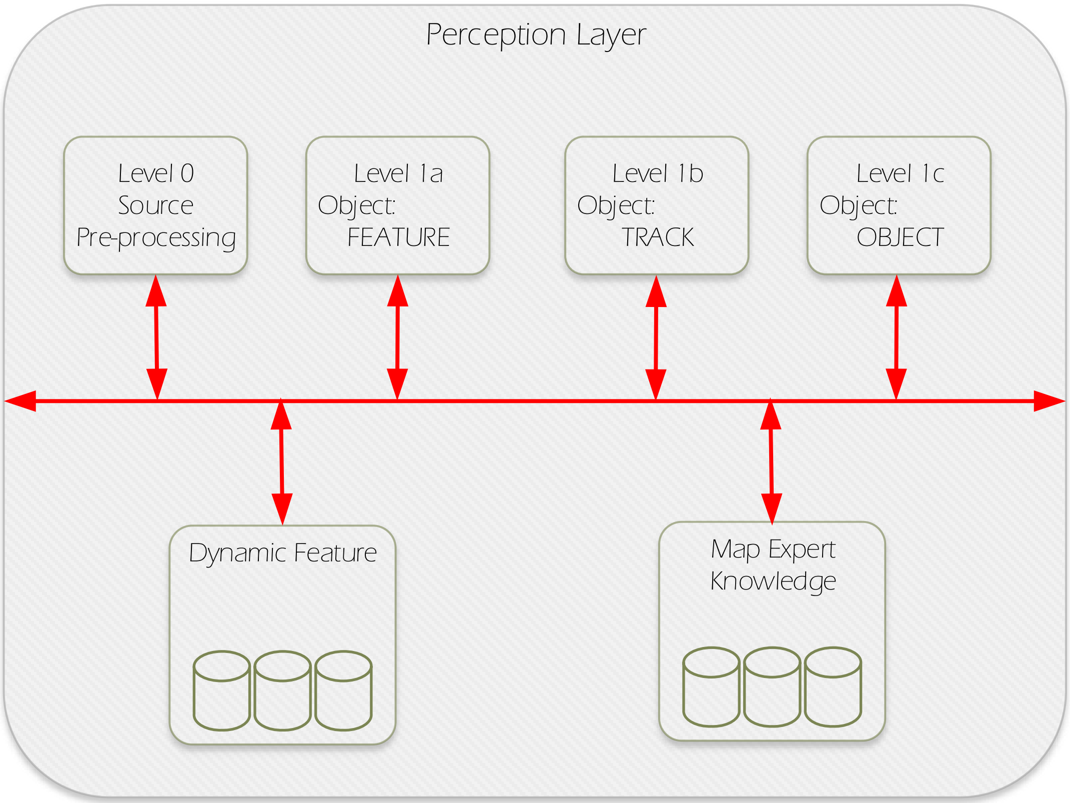

Figure 3.6 Detail of Level 0 and 1 of Automotive Safety JDL model

Again, Figure 3.7 shows a similar structure to the perception layer previously described. Therefore, providing the same benefits as the previous layer. Within this architecture, the system designer can again specify the purpose of the current task or add further tasks to the system at a later time as the requirements of the system objectives or mission change over time.

For instance, we can see from Figure 3.7 below, that the architecture supports as many tasks as required by the designers (level 3). These tasks can be included and not used and only used as and when required depending on the current hardware capabilities of the platform in question or the current mission objectives in place.

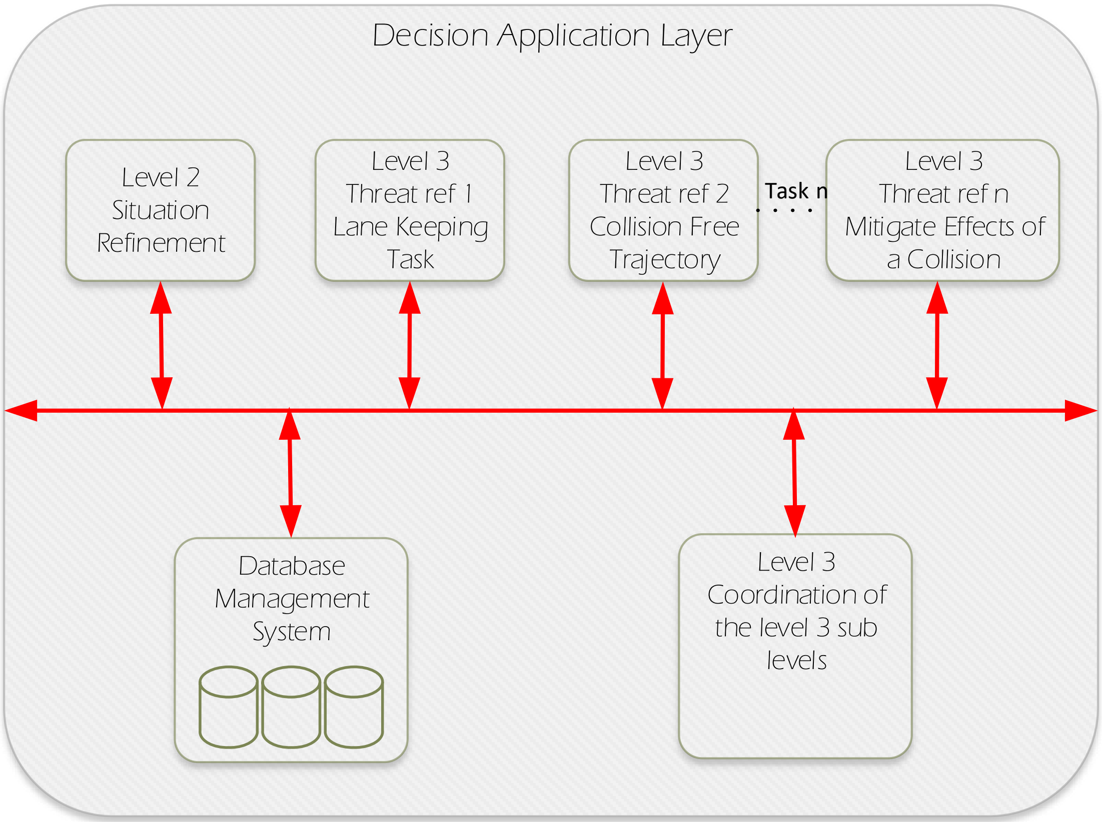

Figure 3.7 Detail of Level 2 and 3 Decision Application Layer

Hence, whilst the entire system does include some trade-offs it can also offer an extremely detailed and more importantly flexible, scalable sensor fusion design approach.

Table 3.4 provides the critical analysis of the revised JDL Model for Automotive Applications architectural approach, highlighting the benefits and constraints of the architecture.

Table 3.4 Benefits and Constraints of the Revised JDL Model for Automotive Applications

Benefits	Constraints
• Level 2 and 3 of this model allow for considerable flexibility within the architecture for different types of objectives and or threat recognition based on the received information from the previous layers' fusion process (levels 0 and 1), • The model clearly provides great flexibility within each of the 3 layers for the development of a sophisticated multipurpose (multi role/capability) systems architecture, • Given that the model had been designed with not only automotive applications in mind but also for the use of multiple sensing devices it is directly relevant to our investigation. Whilst also providing the exact support for the architecture we are researching, • Internal layers do support concurrency within each of the highest-level layers (1, 2 and 3).	• Requires the execution of each of the three hierarchical layers to be performed in order therefore reduces the flexibility of implementation options by not allowing for true concurrency, • Omitted from this research is the JDL Level 4 module which incorporated system resources (CPU, memory and bandwidth) management and sensor task allocation. It is not clear as to why this is the case except the authors state that due to the JDL Level 4 module not being a direct art of the fusion processes it had been omitted from the research. However, this type of resource management would absolutely be necessary within any application of this architecture and therefore would require further investigation and development.

3.3 Review Sensor Fusion Design Topologies

3.3.1 Centralised Topology

Figure 3.8 describes a centralised sensor fusion topology [52]. Generally, it is considered that the advantages of a centralised fusion architecture are that all of the fusion occurs within a central processing block. Therefore, the solution could be considered optimal assuming data alignment is performed correctly and time to transfer data is not significant.

However, depending on the application of the system the amount of data needing to be processed can become significant, removing the system's ability to perform in a timely manner. For example, using this type of architecture to fuse data from vision systems may not be appropriate due to the high bandwidth requirements of visual data transfer [52].

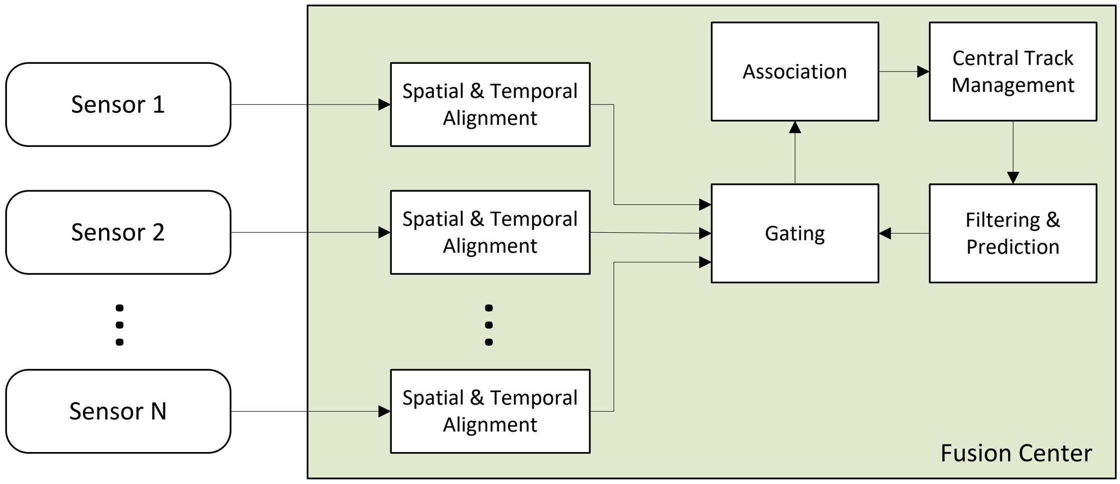

Figure 3.8 Centralised fusion architecture, Lytrivis, Amditis and Thomaidis [52]

3.3.2 Distributed Topology

This design approach (shown in Figure 3.9) allows for each sensor node to pre-fuse local data (allowing for some sensor autonomy) before sending the already partially fused data to the central fusion algorithm. The benefits include lower processing cost on the core fusion process, allowing higher bandwidth for the entire system. Constraints include possible sensor inaccuracy as the fusion occurring at the sensor level is not based on all readings available to the system as a whole [57].

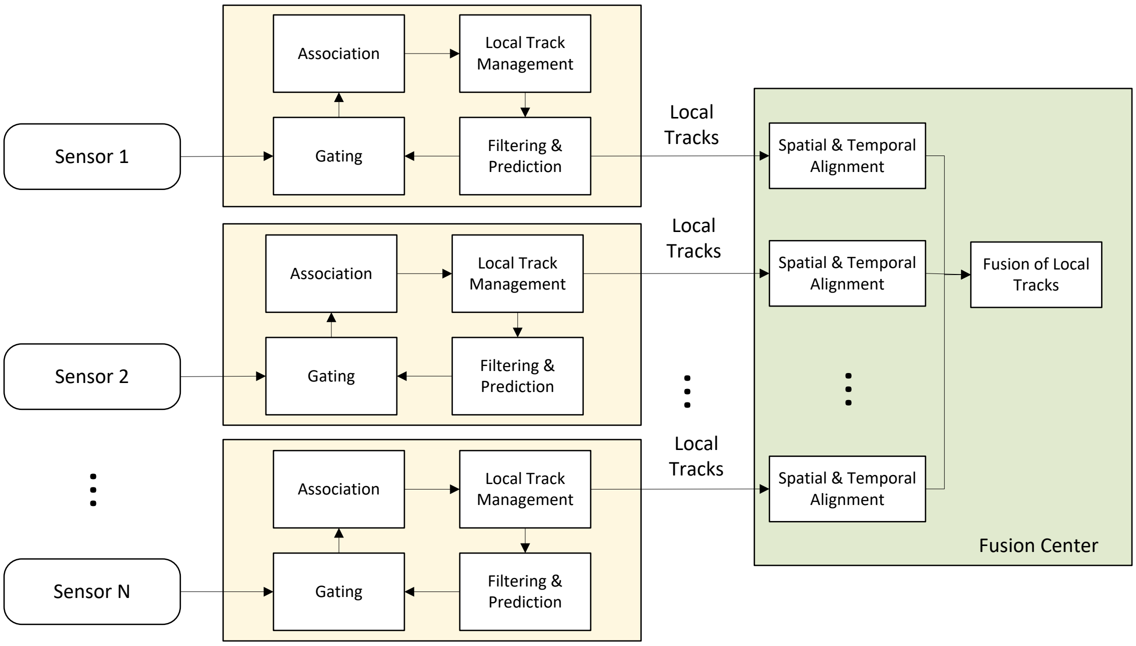

Figure 3.9 Distributed fusion architecture, Lytrivis, Amditis and Thomaidis [52]

3.3.3 Hybrid Topology

Figure 3.10 illustrates a hybrid sensor fusion topology, as the name suggests, this design approach is a combination of both aforementioned architectures. Hybrid design contains many of the beneficial characteristics of both centralised and distributed whilst attempting to mitigate the constraints of each, however system complexity can increase [52].

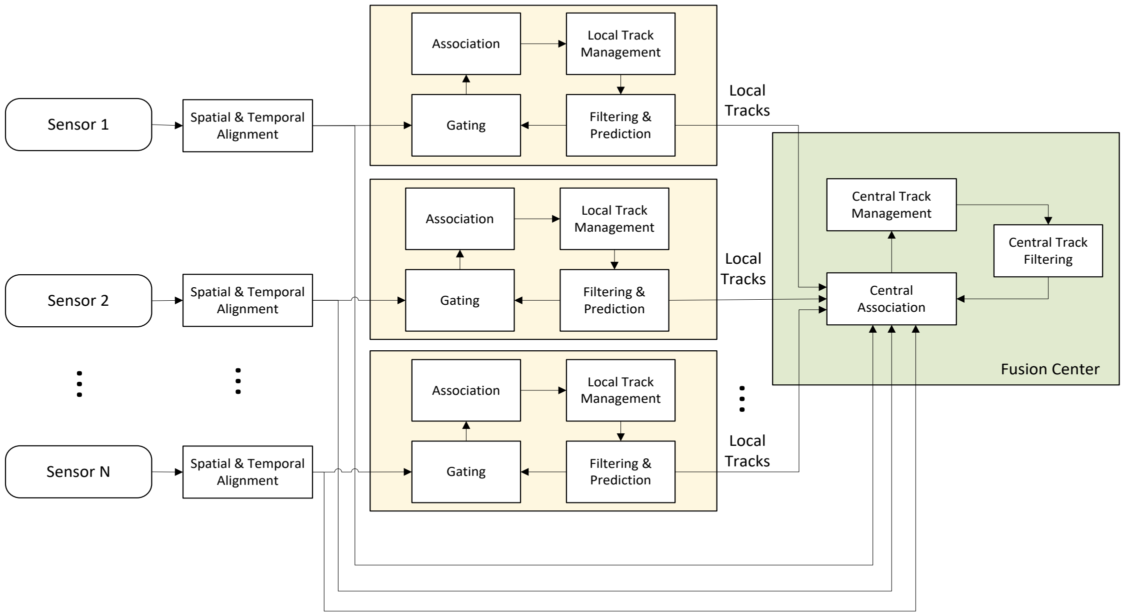

Figure 3.10 Hybrid fusion architecture, Lytrivis, Amditis and Thomaidis [52]

3.4 Review of Automotive Bus Technologies

Provided in the following list below is a brief overview of the current communication protocols currently found within modern automotive vehicles. An introduction to the protocols is provided but primarily this work is concerned with the data structures of a given protocol and any necessary protocol command and control structures / frames. The focus for this review however is interested in protocols that common sensing technologies utilise to distribute sensor data.

3.4.1 Controller Area Network (CAN)

Development of the CAN standard began in 1983 by Robert Bosch GmbH and was officially introduced in 1986 at the Society of Automotive Engineers (SAE) conference held within Detroit [58]. By 1991 CAN 2.0 (ISO 11898 family) was released and remains a dominant bus protocol throughout the commercial automotive industry. Variations of the CAN protocol standard include, ISO 11898-3 low data rate, ISO 11898-2 high data rate, ISO 11898-7 Controller Area Network Flexible Data (CANFD) and Time Triggered Controller Area Network (TTCAN) ISO 11898-4 [59, 60].

Generally, the most commonly used CAN protocol specification in modern automotive applications is the high data rate ISO 11898-2 standard with rates up to 1 Mbit/s up to approximately 40 metres in bus length.

Figure 3.11 describes the basic overview of a CAN network bus which consists of multiple CAN nodes (often called stubs) attached to the main bus. Essentially, the CAN bus (physical layer) consists of two wires described as CAN_H (CAN high, recessive) and CAN_L (CAN low, dominant). This refers to the level state of the bus in terms of voltage CAN_H logical state of 1 and CAN low logical state of 0. CAN protocol operates on an event driven basis.

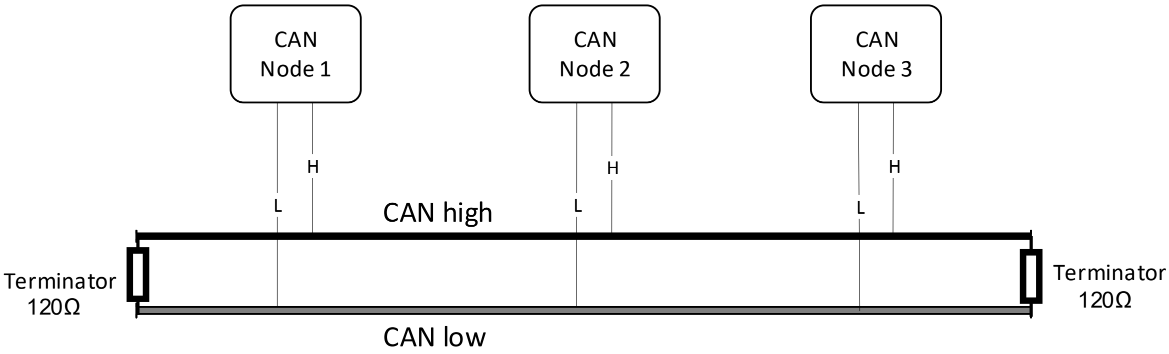

Figure 3.11 Controller Area Network bus schematic, adapted from [60]

3.4.2 CANFD

CANFD is an extension built on the original CAN protocol, developed in 2011 and released in 2012 by Bosch, CANFD (ISO 11898-7) provides additional capabilities over the original CAN protocol. CANFD offers significantly higher bandwidth (up to 12 Mbit/s in the data phase) and larger frame payload of 64-bits in length in contrast to 8-bit length of the standard CAN specification (ISO 11898-2). This is a direct response the automotive industry needs for increasing data rates and size requirements as modern vehicle functions and electronics increase [61].

As the name suggest CANFD has a flexible approach to data transmission, if the bus is empty then data rates can far exceed standard CAN.

3.4.3 TTCAN

Time Triggered CAN is an extension to the CAN protocol, ratified in 2000 as ISO CD 1 1898-4. Developed to provide support for emerging automotive functions and technologies such as drive by wire and cruise control.

Being fully compatible with CAN, TTCAN is designed to synchronise all nodes on the bus. This is achieved by a master time node repeating a special CAN message described as the reference message which resets the cycle time for each node on the bus. Thus, achieving node synchronisation [62].

3.4.4 J1939

J1939 (SAE J1939) is a higher layer protocol built on CAN 2.0b, designed primarily to allow for more complex messages. Widely used within the heavy vehicle commercial industry for collecting and monitoring vehicle status and operational data regarding i.e., engine status and fuel usage.

3.4.5 FlexRay

Originally developed by the FlexRay consortium (which has since disbanded) FlexRay is now an ISO standard. Comparable faster than CAN or TTCAN and with greater reliability and safety critical features. Although FlexRay is more expensive than CAN or TTCAN it does offer greater determinism than TTCAN with larger messages and data rate.

3.4.6 Local Interconnect Network (LIN)

Considered a low cost, simple, bus network designed to form sub-networks between components, ECUs and specific functions (i.e. electronic door locking mechanisms).

3.4.7 Ethernet based technologies

Primarily the bulk of infotainment technologies are implemented utilising standard Ethernet protocol. These are ultimately already adaptable to the proposed sensor fusion framework utilising DDS as a data transfer protocol presented within this research.

More general information regarding the network technologies described above can be found here [63].

3.5 Related Work

The following sub-section provides an overview of future vetronics approaches and common Local Situational Awareness (LSA) systems found within military land systems. In addition, an overview of past COTS technology integration within the military domain is presented. Finally, this section provides supporting information regarding the relevant sensor fusion process behaviour to complement the architecture review presented within this chapter.

3.5.1 Software Defined Vehicle

Supporting the development of fully autonomous vehicles discussed within the introduction of this chapter (and briefly introduced within Chapter 2, section 2.2.1 What is Vetronics) are new electronic architectures and approaches to software / function integration. The automotive industry is recognising that new approaches to future hardware / software implementations are necessary to provide the functionality required of modern autonomous vehicles [64]. The need to support various software components and sensing technologies has increased significantly over the last decade, coupled with the expectations towards requirements for software updates more often over the air. Figure 3.12 highlights this trend, as automotive function complexity increases therefore the required processing power also increases.

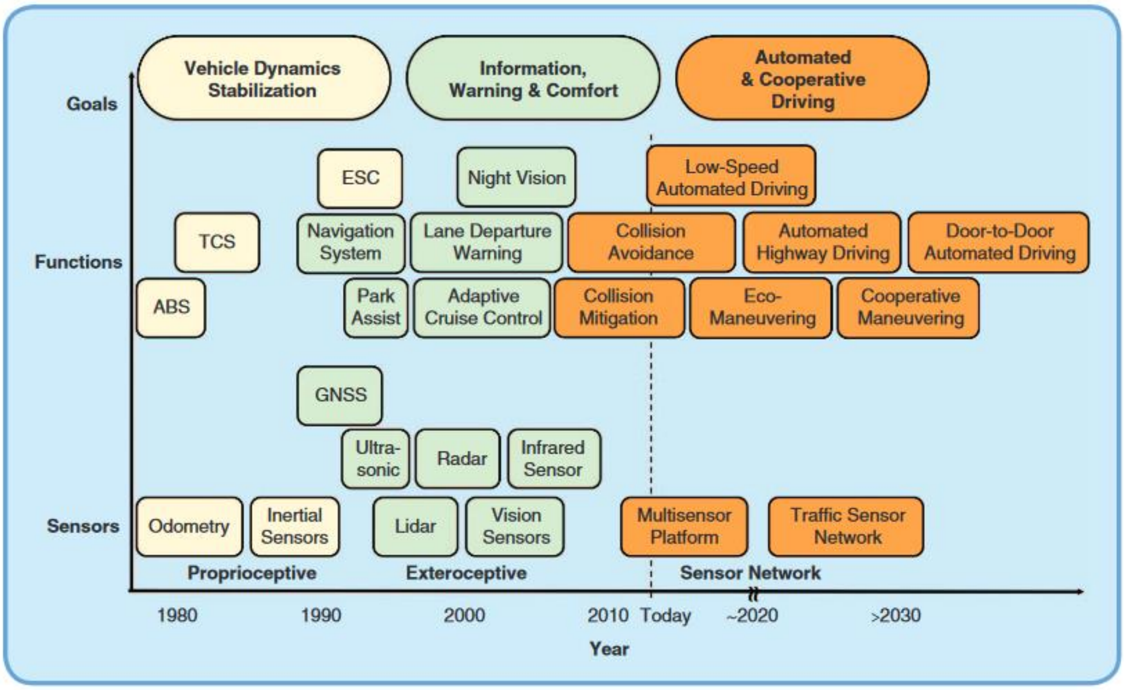

Figure 3.12 Past and potential future evolution towards automated cooperative driving [65]

To meet these growing requirements, new approaches are required for the design and implementation of processing platforms and software architectures. The GVA is an excellent example of a generic architecture design that can be used across multiple platforms (e.g., different land vehicles form small UGVs to large, mounted combat systems) without having to redesign any component (as discussed within Chapter 2).

Whilst the commercial automotive industry is compelled to drive down costs wherever possible it is becoming recognised that a move to a common architectural approach would be of significant commercial benefit, moreover current computational architectures are becoming impractical to implement. Figure 3.13 describes BMW's future expected concept for vehicle computational processing architecture [66].

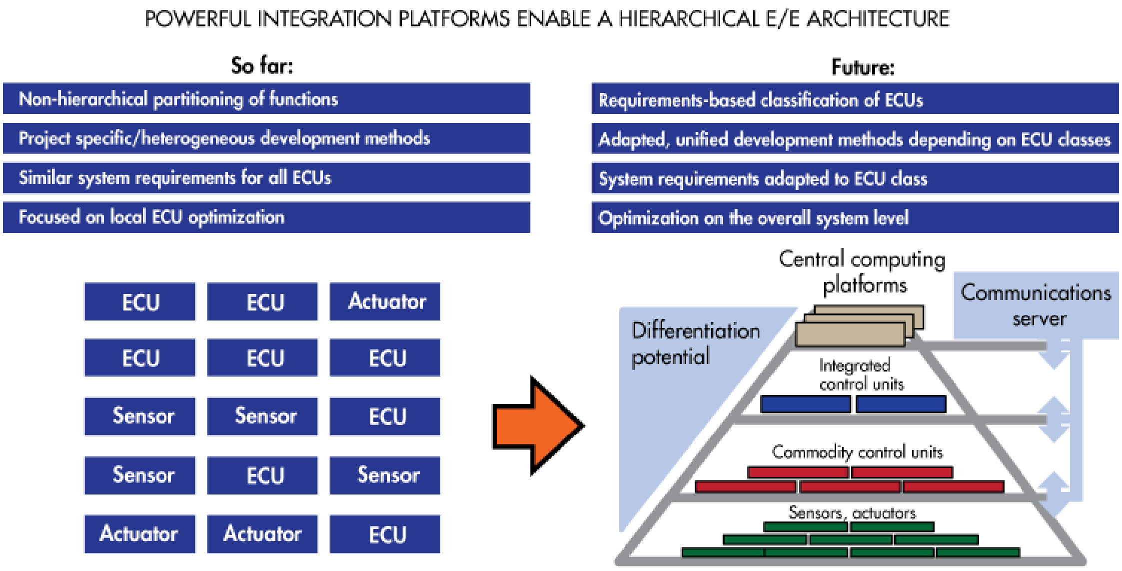

Figure 3.13 BMW's future hierarchical electronic architecture [66]

3.5.2 Mounted Close Combat Local Situational Awareness Systems

Typically, Local Situational Awareness (LSA) mission systems comprise multiple camera / optical based technologies, primarily for long range thermal imaging or laser pointing target acquisition. Usually, these camera systems have a high financial cost (high grade expensive optics / hermetically sealed housing), can be heavy (3 kg – 50 kg) and offer less than ideal resolutions (i.e. 976 px * 582 px). The latter point regarding resolution is of importance, as many LSA systems comprise primarily of camera-based technologies. Whilst these technologies can offer increased visibility for a human operator, machine learning and video frame analysis for the identification of objects / threats produce higher accuracy when resolution is increased (i.e. more pixels to analyse therefore error rate for inferences based on a single image frame is reduced) [67].

LSA systems on current MCS are not designed for high resolution short range situational awareness (1 m – 50 m) and critically they are designed as tactical situational awareness technologies, identifying targets or threats within the 100 m to 1 KM range. They are not designed to offer close-range high-resolution views of current surroundings. Of course, sub-systems designed for autonomous commercial vehicles are designed for exactly that use case. Not only do commercial autonomous systems view the environment in high detail utilising multiple sensing technologies, critically (to the military use case environment) these systems using sensor fusion (as discussed in previous chapters and explored fully in the next chapter) have a complex understanding of the context of objects, that is, the vehicle understands what objects are and therefore what their likely behaviour will be (i.e. a person on a bike will behave differently to a person on foot or a bus) [68].

It is clear that this contextual perception derived from inferences made by the specific sensor fusion algorithm could be modified to be utilised within the military field of operations to monitor civilians, identify potential threats or allow the crews to manoeuvre the vehicle safely within a complex urban environment without coming out of under armour.

3.6 Conclusion

Automotive technologies, such as ADAS, demonstrate capabilities that can potentially enhance the situational awareness, survivability and effectiveness of military vehicles. However, since different manufacturers follow different design processes that suits their individual business needs, the integration approach for those technologies is not standardised.

For example, in some cases individual sensors (offered as COTS products) include the processing intelligence within the sensor package as a standalone product. Whilst, in other cases sensors are provided along with an Electronic Control Unit (ECU) that is used to integrate, process and fuse data from multiple sensors. The specifics of how the different components of ADAS (sensors, ECUs and HMIs) are arranged and the level of integration with the rest of the vehicle architecture are decided by OEMs based on their specific civilian automotive scenarios. Hence, automotive sensor fusion is not a COTS product and exploiting it will require developing/tailoring the capability for military vehicles.

This presents a challenge if such technologies are to be integrated into military vehicle architecture in an efficient and unified approach, in particular, if sensors/components are sourced from different suppliers. A possible solution to this challenge is to borrow the paradigm of smartphone development. In such a paradigm, the sensor fusion process can be developed as a software application without requiring detailed knowledge of the sensors through hardware abstraction. This sensor abstracted fusion paradigm is depicted in Figure 3.14.

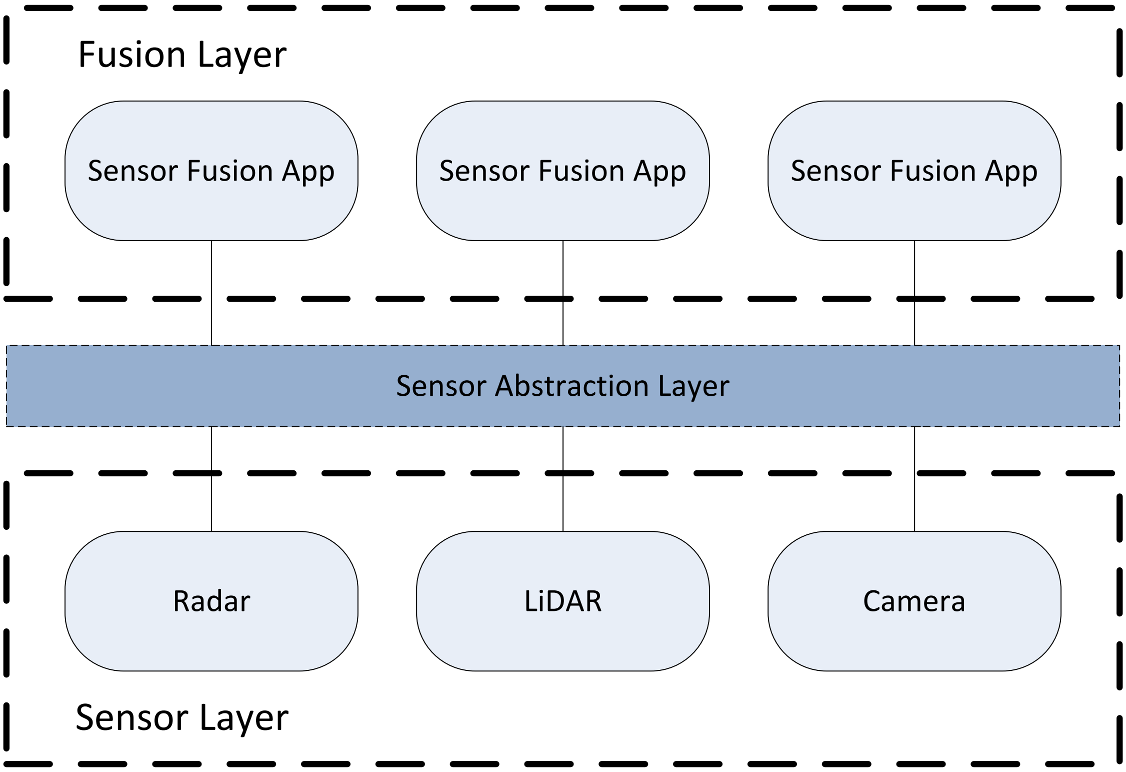

Figure 3.14 Sensor abstracted fusion paradigm

In order to investigate the efficient and cost-effective exploitation of automotive technologies, the proposed paradigm will be explored, and will consider the following key aspects:

- Integration of automotive technologies in military vehicle architecture (e.g. Generic Vehicle Architecture) – consideration of modularity, abstraction, etc;
- Development of sensor fusion architecture for the integration of COTS automotive technologies.

Table 3.5 (on the following page) describes in more detail the high-level considerations to be made for integrating automotive technologies into military vehicle architectures.

Table 3.5 Integration of automotive technologies in military vehicle architectures high level considerations

Considerations	Comments
Integration	• Careful analysis of candid technologies is required to determine the level of integration and exploitation supported by each technology, it is also necessary to determine the integration requirements, particularly in terms of data and power, • The above analysis also aids in understanding the type/extent of exploitation that can be achieved in a cost-effective manner, • The current Generic Vehicle Architecture (GVA) Land Data Model (LDM) sensor data fusion module is at low maturity, • It is envisaged that this module should be further developed in conjunction with the GVA harmonised sensor fusion electronic architecture testbed.
Sensor fusion	• Sensor data fusion is an attractive mechanism for achieving both additional capabilities and improving existing capabilities, • In particular, fusion is used to provide assurance in the validity of a perceived state, hence improving sensor data reliability and therefore platform safety/survivability, • Sensor fusion can be used to infer information that cannot otherwise be determined or be difficult to determine, • Commercial sensors can be integrated to provide situational awareness of surroundings and or events with relatively low costs (especially after the initial design of an electronic architecture to support them), • For advanced fusion systems/capabilities significant investment would likely be necessary for the research, design and development of these fusion systems. The more advanced the capability the higher the development and design costs will likely be.
Security	• When integrating commercial sensing technologies into military vehicles node security is critical, • Dismounts are becoming another source of sensor data (human sensor), providing the land vehicle with additional sensor information from the dismounted soldier’s equipment, transmitting this data securely is obviously critical.

The following chapter will provide a detailed technical analysis of modern automotive sensing technologies and cross reference these technical benefits and constraints when operating within the constrained environment of military land platforms. This will take the form of a two-part study, designed to assess the capabilities and applicability of each family of sensing technologies with current and future military operating environments in and around military land platforms.

4 COTS Sensing Technologies Within Mounted Combat Systems

4.1 Introduction

In this Chapter, technologies from a selection of major automotive suppliers are reviewed. A comprehensive two part study has been conducted of current automotive sensing technologies and ADAS technologies, to assess their capabilities and applicability within military land platforms to enhance situational awareness for crews of MCS [69]. The results of this analysis are presented here along with truncated (full use cases can be found in Chapter 5 and are referenced when applicable) use case examples which were presented to and reviewed by the UK MoD.

Study 1 – A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is conducted for each of the main automotive technologies that are used for perception and situational awareness within autonomous / semi-autonomous commercial automotive vehicles. These main technologies are Radar based, LiDAR, UltraSonic, Leddar and video systems. This analysis assesses the potential of exploiting these technologies in military vehicles. Finally, a summary is provided highlighting key benefits and constraints of utilising such technologies within MCC.

Study 2 – A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis is conducted on a wide range of key automotive ADAS sub-systems. The ADAS sub-systems analysed are the following, autonomous emergency braking safety, parking assist and rear cross traffic alert sub-systems. These sub-systems were selected based on the use cases developed during this research, reviewed, and approved by the UK MoD. Finally, a summary is provided highlighting key benefits and constraints of utilising such technologies within MCC.

4.1.1 Proposed Operational Concept for Military Land Platforms

The use cases presented within Chapter 5 (section 5.3) for general MCS activities have been defined to underpin / map the requirements for different activities to specific sensing technologies. The diagram presented below (Figure 4.1) describes one proposed scenario for future land systems utilising a mixture of COTS and proprietary vehicle sub-systems to provide enhanced safety through increased situational awareness in the connected Internet of Battlefield Things (IOBT).

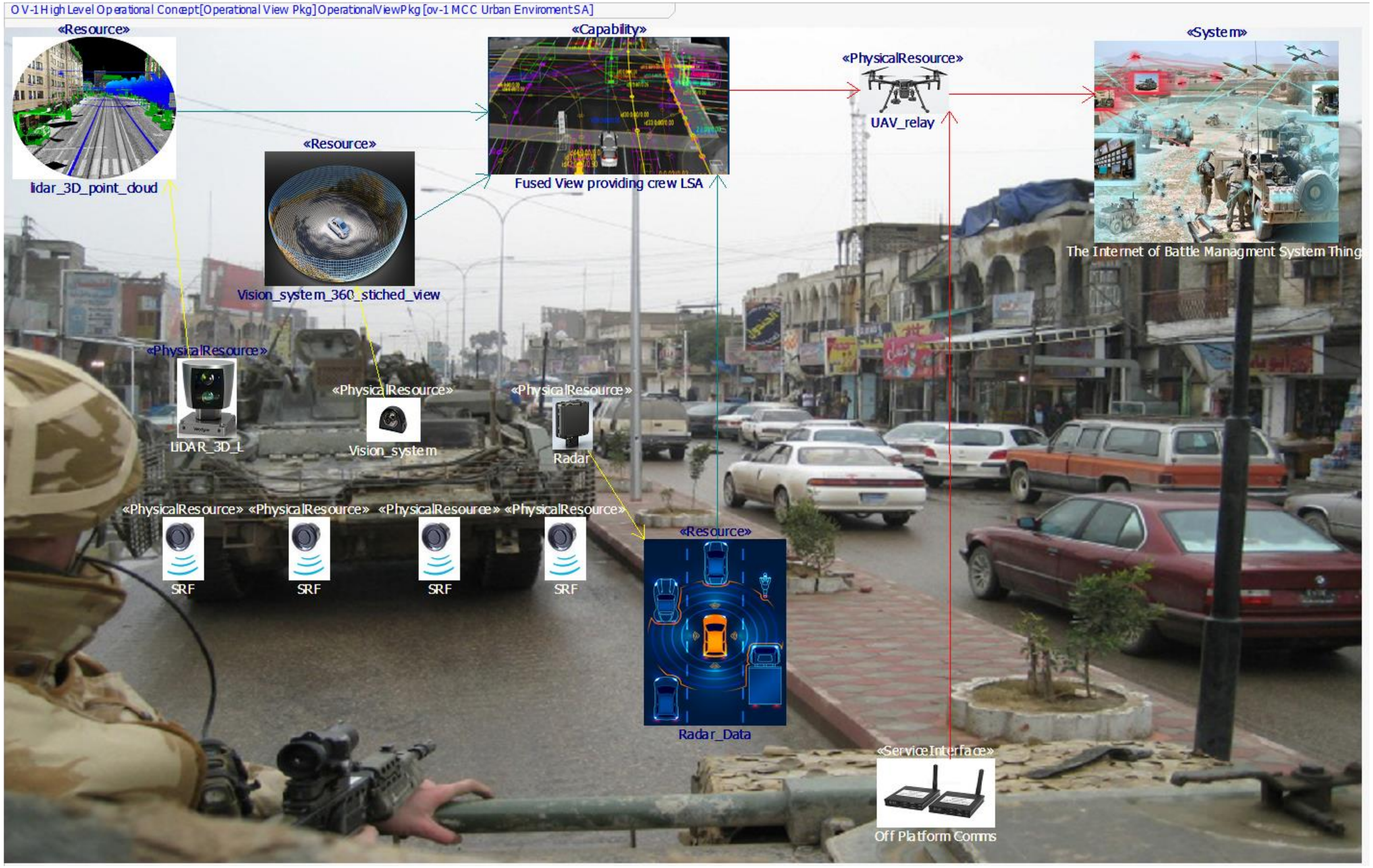

Figure 4.1 Operational view of proposed system (current / future)

Operational View of Proposed System

The theoretical operational view (Figure 4.1), provides one utilisation of automotive COTS sensing technologies within current military land platforms and is broken down into the following components within Table 4.1 below:

Table 4.1 Operational view component breakdown

Operational view component	Description
Physical resources	These are sensing technologies themselves, comprising of: • Sonic Range Finder (SRF), • 3D large LiDAR unit (i.e. Velodyne HDL-64E), • Vision system (i.e. ASL 360), • Radar (i.e. ARS 408-21).
Data Resources	This describes the sensor data that is being made available to the vehicle for processing, some data may already be pre-processed, such as: • Stitched video data frames, • Radar tracks data, • 3D LiDAR point cloud. Simple distance data would also be available (i.e. data sent from the SRFs).
Capabilities	Here the capabilities provided by a fused view of all currently available sensor data is represented.
Service Interface	This represents the off-platform COTS technologies such as Dedicated Short-Range Communication (DSRC), supporting standards such as Wireless Access in Vehicular Environments (WAVE protocol suite).
System	The overall situational awareness for a future Internet of Battlefield management things (IOBT).

4.1.2 Sensing Technologies Analysis Methodology

Below provides a brief breakdown of the methodology used to assess the applicability of modern sensing technologies within military land platforms for enhancing local situational awareness.

Step 1: Initial use cases / capability aspirations have been developed and defined (5.3 UK MoD Collaboratively Developed Use Cases) in conjunction with and verified by the UK Ministry of Defence technical representatives and UK MoD service members who operate military land platforms.

Step 2: Definition of activities and required services based on the use cases presented within step 1 above. These in turn, are mapped to specific land platform activities which finally are mapped to functional requirements.

Step 3: Held meetings with Tier 1 suppliers in this case Continental Automotive Group.

Step 4: All of the above is considered, and the following analyses are undertaken:

- SWOT,
- Utility assessment,
- Cost assessment,
- Readiness assessment.

Step 5: All results collated into a coherent form and utilised to inform the design of CTIL, GSFEA frameworks and inform safety / security considerations.

4.2 Study 1 – Analysis of Key Sensing Technologies for Automotive Systems

The following section presents an analysis of individual sensor technologies, their operational behaviour, and characteristics. Identification of their signal emissions traits and performance metrics is of critical importance within the context of the military domain.

Many performance metrics for all the sensor types analysed within study 1 (i.e. effectiveness and behaviour within a Degraded Visual Environment (DVE)) are derived from discussions with MoD personnel, equipment manufacturers and sensor experts along with sensor data sheets. Meetings took place, for example, with two radar experts within Continental Automotive Group who were questioned regarding the physical parameters of Continental AGs radar EM behaviour within multiple operating conditions.

4.2.1 Radar

Radar (**RA**dio **D**etection **A**nd **R**anging) technology uses radio waves to detect the position, distance and speed of objects [70]. Radar operates by emitting a radio wave through a transmitter, these waves are reflected back by objects. The reflected waves are captured by a receiver and information about the detected objects is deduced based on these reflected waves (e.g. change in signal frequency and round-trip time).

A key advantage of radar technology is that it continues to function in all weather conditions and its performance is not restricted by elements such as fog, smoke, rain or snow. However, radar performance can be limited by material properties. For example, a radar wave is reflected well by electrically conductive materials whereas materials such as plastic and wood are less reflective, therefore can produce erroneous readings [71].

Automotive radars are designed as either short or long range based on their intended application. As the name suggests, short range radar has short range (typically 50 metres) with a wide field of view (typically 60°) and is thus suited for close proximity detection of slower objects and is used for applications such as blind spot detection. On the other hand, long range radar has a longer range (typically 150 metres) with a narrow field of view (typically 15°) and is thus better suited for the detection of distant objects at speed and is used for applications such as forward collision warning.

Examples of commercial automotive radar sensing technologies are described in 10.3 Appendix C: Automotive Sensing Technologies examples, whilst Table 4.2 below presents a SWOT analysis for the potential exploitation of automotive Radar technologies within military land platforms.

Table 4.2 SWOT analysis of Radar technology exploitation in military vehicles

Strengths	Weaknesses

• Detection of position, distance and speed of multiple objects at the same time.
• Can support long detection ranges (up to 200 metres) and wide detection angle (up to 60º).
• Exhibits good performance in DVE.
  o Can operate in dark, fog, rain, dust and smoke.
  o Performance is susceptible to high levels of moisture in the environment (e.g., performance will be lower in heavy rain).
• Radar detections data is often provided over standardised automotive interfaces (e.g., CAN).
	• Commercial radar is often provided with software tailored for specific applications,
	  o Might not be possible to access raw radar data.
	• No security considerations given to commercial radar units as they are not considered to be at risk.
	• Radar with mechanical antenna is susceptible to vibration/shock.
	• Sensors can be relatively expensive to procure in low volumes (about 1,000 Euros a unit for a typical sensor from Tier 1 automotive supplier for order size of 10 units).

Opportunities	**Threats**
• Can see through visual barriers and penetrate some types of matter. o Potentially see-through walls (detect human activity) and ground (detect IEDs). • Radar Cross Section data can potentially be used as an object signature (enabling detection of concealed objects of interest). • Advances in technology are expected to lower the cost of the sensor.	• Radar is an active sensing technology, which makes it possible for specialist equipment to identify the radar sensor signature and locate the vehicle. • Regulation: different radar sensors operate in different frequency spectrums, some of which require a licence to operate in parts of the world.

Radar Utility Assessment

The utility of radar in military vehicles can significantly increase perception and enable the development of enhanced safety and situational awareness capabilities. Radar sensors tend to have good coverage in terms of detection range and angle and are well suited for measuring speed/motion. Its performance in DVE is often regarded as the better one out of the other technologies discussed.

Radar Integration Assessment

Automotive radar is designed to be integrated with other automotive systems through the CAN interface. Data available over the CAN interface is often tailored for a specific application (e.g. long-range detection of vehicles and pedestrians; or detection of objects in blind spots that are in close proximity), this helps reduce the data generated by the radar system. However, some automotive radar sensors do not allow access to raw data, which might be required to support novel applications desired in the military context.

Some radar units accept remote commands to enable/disable the sensor, which is a useful feature in managing the vehicle’s signal emission.

Radar Cost Assessment

The cost of automotive radar varies significantly based on the supplier and the purchase order volume. For example, the unit cost of a radar from an automotive Tier 1 supplier can be about 2,700 Euros if one piece is purchased, while the same radar would cost about 200 Euros per unit if 50,000 pieces were purchased. Therefore, radar is considered a relatively expensive sensor when purchased in low volumes. However, new advances in radar technology and introduction of competitive suppliers indicate significant reduction in future costs.

Radar can potentially have novel applications in the military context. However, this would require engineering effort to identify and assess the technology potential for a specific application. Since radar is a highly specialised field of knowledge, this can significantly increase the cost of adapting automotive radar to military applications.

Radar Readiness Assessment

Radar is a relatively mature technology used in a multitude of applications and its performance/limitation is well understood and verified. Although radar technology is considered a stable technology, new advances in the technology (e.g., design of antenna) are enabling reduction in cost, size and power requirements.

4.2.2 LiDAR

LiDAR (**Li**ght **D**etection **A**nd **R**anging) technology uses light (laser) to scan, profile and map objects [72]. Similar to Radar, LiDAR works instead by transmitting light (continuous or more commonly rapid pulses) over a wide area and analysing the reflected signal.

Key advantages of LiDAR technology are that it provides relatively higher accuracy (able to detect small objects) and data density (richer information about the surroundings); it is faster to acquire and process signals; and is relatively cheaper. However, it was recently demonstrated [73] that a LiDAR system could be tricked into detecting objects that do not exist using an inexpensive kit, which has raised concerns over security.

Both radar and LiDAR types of automotive sensors come in a package that includes the sensor hardware (e.g., transmitter, receiver, antenna, etc.), a Digital Signal Processing (DSP) unit and often a communication controller, commonly a Controller Area Network (CAN) controller.

The DSP unit analyses the reflected signal captured by the receiver and stores that information into a data point. The data points are stored and organised in a coordinate system to create what is known as a ‘point cloud’. Based on the sensor’s configuration, the point cloud can be provided over the network (sometimes referred to as clusters configuration). However, since a point cloud is considered a noisy representation of the surroundings, the DSP can be configured to analyse point clouds to track the movement of objects of interest over time. In such configuration, information about the tracked objects are provided over the network instead of the point cloud (sometimes referred to as tracks configuration).

Examples of commercial automotive LiDAR sensors are described in 10.3 Appendix C: Automotive Sensing Technologies examples, Table 4.3 below presents the analysis for the exploitation of LiDAR technologies within military land platforms.

Table 4.3 SWOT analysis of LiDAR technology exploitation in military vehicles

Strengths	Weaknesses

• 3D representation of surrounding environment,
  ○ Ability to scan, profile and map objects in 3D.
• High resolution and accuracy,
  ○ Can be used for precise navigation and location positioning.
• Can provide 360º view,
• Exhibits good performance in some DVE,
  ○ Can operate in night-time/dark,
  ○ Can operate in moderate amounts of rain, fog, dust and smoke.
• LiDAR data is provided over standardised interfaces (e.g., Ethernet).
	• Detection range can be limited (between 6 and 100 metres),
	• No security considerations given to LiDAR units,
	• Mechanically scanning LiDAR is susceptible to vibration/shock,
	• Current commercial sensors are expensive (between \$8k and \$75k a unit),
	• LiDAR generates large amounts of data, which could increase the bandwidth requirement of the vehicle electronic architecture.

Opportunities	**Threats**
• Can be used to construct a 3D model of the surrounding environment, ○ To support training, strategy development and monitoring change in the environment. • Can be used to understand the geometrical aspects of the surrounding environment (e.g., measure distance between objects), • Advances in solid-state LiDAR are expected to lower the cost (expected to be as low as \$100).	• LiDAR is an active sensing technology that can easily be detected, which makes it possible to identify the LiDAR sensor signature and locate the vehicle, • It has been shown that a LiDAR sensor can be fooled into detecting non-existing objects (please see section LiDAR Spoofing below for further details).

LiDAR Spoofing

The ability to fool a LiDAR system into detecting objects that do not exist has been shown by J. Petit [73, 74]. This is achieved by emitting another laser source in a specific pattern to match the LiDAR unit's receiver. LiDAR operates by emitting a beam of light and then receiving that beam to calculate a distance point in 3 axes, x, y, z. Typical modern 3D LiDAR sensors produce vast numbers of measured points (each related to an x, y, z coordinate) per second, resulting in a 3D visualisation of the scanned area when all points are collated in near real time.

This is a threat that could allow for the manipulation of system behaviour through false readings compromising the safety of the MCS. However, it is noted that the attack had been only carried out on a single specific LiDAR unit (ibeo LUX 3).

Knowledge and understanding of this threat can evolve to not only mitigate its effects but to also provide an opportunity for countering adversarial laser range finding equipment using a similar technique.

It is recommended that if selecting a specific LiDAR model for deployment that Petit's work be understood, and the level of this threat be explored for that specific model.

LiDAR Utility Assessment

LiDAR technology has demonstrated great promise in enabling a 3D perception of the environment around it. The high resolution and precise 360º view provided by LiDAR can aid existing capabilities (e.g., supporting high-precision navigation) and enable new capabilities (e.g., using depth information to understand the geometrical aspects of the environment, which can be used to measure distance between objects). The technology can also be used to construct 3D models of desired environments, which then can be utilised for training, strategy development and environment change monitoring.

LiDAR Integration Assessment

LiDAR data, typically represented in point-cloud format, is passed on to software that saves the data to create a historic record that can be visualised (often in a 3D map fashion). The LiDAR data set/record can be analysed to identify and track objects over time.

The data generated from LiDAR is often large in size and transmitted at a high rate (typically this can be up to 20 Hz [75]), which can create a significant burden on a vehicle's communication network, hence will require careful consideration when integrated into a vehicle's electronic architecture.

LiDAR Cost Assessment

Current commercial LiDAR units are expensive. Most of these sensors have a rotating mechanism and require line of sight (reducing the level of protection), which make these sensors susceptible to failure and damage in the harsh military environment. This can significantly increase the cost of maintaining such capability in the long term.

Nonetheless, advances in the technology, in particular the prototypes of solid-state LiDAR (no-mechanically moving parts), promise significant reduction in cost. This is likely to increase the viability of LiDAR technology application in military vehicles.

LiDAR Readiness Assessment

LiDAR is a rapidly evolving technology with new capabilities constantly being developed and many of its limitations/vulnerabilities still being discovered. Although there seems to be a lack of formal verification of LiDAR performance, its characteristic performance is well understood and with significant efforts invested by the automotive industry the technology is expected to mature rapidly.

4.2.3 Vision Systems

Video cameras have long been used in civilian vehicles for a number of applications. Advanced camera systems are typically used for multiple functions providing a visual aid to the driver (e.g. reversing cameras) or for machine vision (object/pattern recognition). A typical modern automotive camera system consists of an imaging sensor (optics, CMOS lens) and an image processing unit, which performs pattern/feature extraction, object recognition and tracking.

Some multi-function camera systems use a combination of video cameras, radar sensing and data fusion techniques integrated in a single module to support a wide range of applications such as forward collision warning; lane departure warning; adaptive cruise control; pedestrian detection; autonomous braking; and traffic sign recognition.

One of the challenges of using camera systems is that they are susceptible to environmental conditions that can block the camera views and scratch the camera lens, such as dust and dirt.

Examples of commercial automotive camera systems are described in 10.3 Appendix C: Automotive Sensing Technologies examples. The table presented on the following page (Table 4.4) describes the SWOT analysis for the exploitation of vision systems within military land platforms.

Table 4.4 SWOT analysis of vision technologies exploitation in military vehicles

Strengths	Weaknesses

• Primarily a software solution.
  ○ Reduced cost of upgrades/modifications.
  ○ New advances in technology can often be seamlessly incorporated.
• Very cost effective.
  ○ Camera hardware is cheap – most of the cost is associated with the additional software.
• Current technology can detect, track and classify multiple objects.
• Versatile technology.
  ○ Object detection and pattern recognition can be relatively easy to customise to suit application.
• Camera is a passive sensing technology, which helps manage vehicle signal emission.
• High resolution.
• New technology can provide 360º view.
• Camera data is provided over standardised interfaces (e.g., Ethernet);
• New technologies such as Toshiba TMPV7608XBG [76] vision system, have significantly improved night time/low light object detection/recognition.
	• Detection range can be limited.
	  ○ Camera resolution and software performance dependant (the higher the resolution the further object detection can be identified by software).
	• Cannot see beyond the line of sight.
	  ○ Cannot see through non-transparent objects.
	• Exhibits poor performance in DVE.
	  ○ Functionality can be limited in fog, dust and smoke.
	• High-bandwidth cameras generate large amounts of data, which could increase the bandwidth requirement of the vehicle electronic architecture.

Opportunities	**Threats**

• Cameras can be used to aid navigation.
  ○ Detection of landmarks, street signage, etc.
• Can be used to create a historical record of the desired environment to support the detection of changes in the environment.
• Two cameras can also be used to calculate range to an object by creating stereoscopic images [77];
• Can be customised to detect objects of interest in the military context (e.g., flags, characteristic uniform).
• When combined with virtual/augmented reality technology, it may prove possible in the future to provide 360º see-through armour capability.
	• Vision systems are prone to failure in harsh environments.
	  ○ Dust/dirt on camera lens will hinder the system's operation and would require regular cleaning.
	  ○ Camera lens is susceptible to damage from dirt and gravel.

Vision Systems Utility Assessment

The use of cameras in vehicles is well established, as it is a versatile solution for improving the situational awareness of the operator. Recent advances in automotive vision systems have demonstrated their power in interpreting scenes and classifying objects.

A modern automotive vision system comes with the camera optics, dedicated processing hardware and software algorithms in one unit. This allows upgrades and fixes to be applied through a software patch as far as allowed by the hardware limitations. In most cases, an automotive vision system can be customised to a military application through software modifications.

Vision Systems Integration Assessment

High-resolution cameras generate vast amounts of data and often at high rates (this is one of the reasons real-time automotive vision systems include dedicated image processing hardware capable of handling large data). If the camera data is required to be recorded or forwarded to other systems, this can create a heavy load on the electronic storage device and/or the communication network.

Vision Systems Cost Assessment

Cameras are the cheapest sensor to acquire from a large and competitive supplier base. Being a primarily software solution (efficient approach to upgrades, fixes and functionality modification), makes vision systems a very cost-effective option.

Vision Systems Readiness Assessment

The application of camera technology in vehicles is rapidly evolving and the automotive industry is making significant investments into improving and maturing the technology. However, currently there seems to be a lack of verification of camera software use in high-criticality applications as it is difficult to cover all possible test scenarios and perform corner-case testing.

4.2.4 Navigational Aids Technologies

Traditionally, automotive navigation systems were standalone units based solely on GPS (Global Positioning System) technology. As an added feature to those standalone units, Traffic Message Channel (TMC) technology was used to deliver road traffic information over radio to the navigation system, in order to help improve route calculation and avoid traffic delays.

As vehicle electronics advanced the navigation system was integrated into the vehicle infotainment (information and entertainment) system. This integration has enabled techniques such as dead-reckoning [78] to be utilised to provide better coverage and overcome the limitations of GPS (signal weakness in urban environments and inside buildings/tunnels). In automotive dead-reckoning, information such as speed and steering direction are collected from motion sensors already present in the vehicle and integrated with the GPS data (when available) to provide a combined position fix.

During the past five years there has been a major shift towards the integration of smart phone technologies into internet-connected vehicles. This results in the provision of rich services and in particular, dynamic navigation that is constantly up to date with the road network condition. One key technology that is showing great promise is the dynamic route navigation based on community monitoring and updates (crowdsourcing [79]). This technology is pioneered by Google and Waze (acquired by Google in 2013).

Waze works by gathering traffic information from each device that runs the Waze software. The information gathered in the background (without user input) includes the user's driving time, speed and behaviour, which in turn is used to infer traffic conditions and present that information back to users in real-time [80]. The users can also actively participate in reporting traffic incidents, road closures, police/speed traps, hazards/events, etc. Additionally, users can edit maps and record road conditions using an online web-based tool.

Such technology can be exploited in the military context whereby gathered intelligence and information from the Battle Management System (BMS) can be integrated in real-time into the navigation application. Hence enabling intelligent dynamic route navigation that avoids roadblocks/traps and improves the safety of the land platform and hence the crew/mission etc.

Other novel technologies such as indoor positioning systems (e.g. Wi-Fi location positioning [81] and geo-magnetic positioning [82, 83]) fall outside the scope of this automotive technologies review. However, these technologies show great promise for position tracking of both mounted and dismounted systems in urban environments.

4.2.5 Sensor Role Identification

Table 4.5 below describes brief examples of commercial sensing technologies being exploited within military land platforms within their intended operationally parameters. Further use cases have been developed highlighting specific use cases within military land platforms and are provided within Chapter 5.3 UK MoD Collaboratively Developed Use Cases.

Table 4.5 Exploitation examples - utilising commercial technology for its intended application

Capability – Technology	Example Exploitation Scenario
A 360º bird's eye view of vehicle – stitching of multi-camera video streams	Crew on a mission to secure an urban site. Red force is on foot sneaking up on the vehicle in an attempt to attach an explosive belt to the turret or petrol-bomb the engine. Crew use the 360º video to identify and track opponents and take evasive action.
Round the corner view – wide angel/fisheye cameras mounted on vehicle edges or protruding rods.	Crew driving in narrow urban streets. Red force is hiding in a sidewalk in an attempt to launch a surprise attack on the vehicle. Crew use the round the corner view to detect and identify threat before the vehicle is exposed to the threat.
Surround view – multiple cameras providing visibility of blind spots.	This can be used in multiple scenarios (peacekeeping, service, etc.) to enable driver autonomy at instances where the driver usually requires assistance (e.g. so that the driver is able to safely park/reverse the vehicle with no input from other crew members).
Dynamic navigation with traffic/situation monitoring – GPS/INS and vehicle connectivity.	Vehicle is en-route to its destination but there is a roadblock ahead. The dynamic navigation system detects the roadblock and provides the crew with alternative routes. Externally collected intelligence is used to advise crew on the optimal route to take and if a route could lead into an ambush or other hazards. Location of blue and red forces can also be shown on the navigation system to improve situational awareness.

Table 4.6 below presents brief; example use cases for commercial technologies exploited within military land platforms beyond their intended application.

Table 4.6 Exploitation examples - exploiting commercial technology beyond its intended application

Capability – Technology	Example Exploitation Scenario
Camera based detection / classification of subject of interest – high-resolution cameras with image recognition software tailored to the patterns desired to be detected.	Crew is on a mission to secure an urban site (cluttered environment). The crew uses the camera system to scan the surroundings in search of subjects of interest. The system identifies those subjects based on visual cues (e.g. characteristic uniform, mark/logo, etc.). **Assumptions:** This scenario assumes that it is possible to extend the image recognition/feature extraction of a high-resolution automotive camera to be able to detect and classify subjects of interest based on predefined visual cues.
Camera based location positioning – cameras and software to detect landmarks and match with a database of geo-referenced images.	Crew is on a mission in a dense urban environment where GPS signal is denied/jammed. The camera system is used to scan the surrounding area to identify points of interest that can be used as location identifiers (e.g. monuments, hospitals, churches, mosques, etc.) as well as signage (e.g. street name signs, address signs, retail shop/supermarket signs, etc.). **Assumptions:** This scenario assumes that it is possible to extend the image recognition of an automotive camera to be able to identify landmarks and other points of interest as well as recognise signage text and symbols. It is also assumed that the system is able to identify and track over time the direction and location of detected objects in order to infer vehicle location. Another assumption is that the points of interest are pre-known and programmed into the system.
LiDAR based location positioning – 3D LiDAR sensor and software to match LiDAR pattern with a 3D LiDAR map.	This scenario is similar to the previous one, where LiDAR sensors are used instead of a camera. 3D LiDAR can model and map the environment around the vehicle with good accuracy. When combined with GPS and/or camera-based location positioning (sensor fusion), LiDAR can provide very high accuracy positioning. **Assumptions:** LiDAR location positioning requires premade high-resolution 3D maps as a reference.
LiDAR based 3D modelling of desired environment – 3D LiDAR sensor and software to construct 3D model from recorded LiDAR data.	Recording of LiDAR data to create a 3D model of the environment, which can be used for training, strategy development and monitoring change in the environment (e.g. detecting when part of the road is dug up indicating possible IED). Through techniques of sensor fusion, the 3D model can be textured with captured camera images to provide a realistic model.
Object detection and classification based on Radar Cross Section (RCS) – radar sensor.	Vehicle is on a mission to secure an urban site. Red force is on a rooftop and equipped with a rocket launcher. The system detects the RCS signature of the rocket launcher and warns crew of the threat. **Assumptions:** Use of RCS as an object signature is experimental. Current automotive radar sensors are not tailored for this type of application and therefore are unlikely to exhibit reliable performance in such applications.
Human activity detection through barriers (walls) – radar sensor.	Vehicle is on a mission to secure a deserted built-up site. Red force is hiding behind a wall preparing to launch an attack. The system uses radar sensors to scan for human activity behind walls. The system detects red force activity and warns the crew of the threat. **Assumptions:** Although radar waves can be used to detect human activity behind walls, current automotive radar sensors are unlikely to support such a feature as it requires different operating frequency and power.
Landmines / IEDs detection – LiDAR/radar sensor.	Vehicle is driven around a city when it is detected that parts of the road have been modified since last observation/mission. Accordingly, an IED threat is suspected and crew use the system to scan for potential buried IEDs. **Assumptions:** Although radar waves can be used to detect IEDs buried underground, current automotive radar sensors are unlikely to support such features as it requires different operating frequency and power. However, it is also feasible to use priori knowledge of terrain (from detailed LiDAR 3D map) to assert using pattern matching that a surface has been recently modified. Providing possible indication of IED placement.

4.2.6 Sensor Role Classification

The following table (Table 4.7) presents the role selection for various sensing technologies. It is intended to show the potential use cases under any given activity for each sensor type (roles are based on sensor physical sensing attributes i.e. electromagnetic, light based or sound wave-based sensing). The assessments and classifications described were obtained by using sensor data sheets, experience with using sensor types and discussions within the UK MoD personnel and industry partners (i.e Continental AG [84]).

Table 4.7 Sensor Role Analysis and Classification

Sensor Fusion Use Cases						
	Use Cases					
	Manoeuvring		Pattern Recognition		C-IED	
Tasks / **Sensor / Other Data**	Object detection	Localisation Positioning	Behaviour Monitoring	Facial Recognition	Terrain analysis	Ground Penetration
Radar	✓	✓	✓	✗	✓	✓
LiDAR	✓	✓	✓	✓	✓	✗
Vision system	✓	✓	✓	✓	✓	✗
Ultrasound	✓	✓	✗	✗	✗	✓
LED range finder	✓	✓	✓	✗	✗	✗
IR	✓	✓	✓	✗	✓	✗
Dismount	✗	✓	✓	✓	✓	✗
GPS	✗	✓	✗	✗	✗	✗
Off Platform Data	✗	✓	✓	✓	✓	✗
Inertial Navigation System	✗	✓	✗	✗	✗	✗
Meteorological Sensors	✗	✗	✗	✗	✓	✗
Acoustic Sensors	✗	✗	✗	✗	✗	✗

4.2.7 Summary of Study 1

Commercial sensing technologies demonstrate clear benefits in addressing the safety and situational awareness challenges that often confront MCS in complex urban environments. Not only this, procuring sensing technologies closely aligns with the ethos of the GVA approach, promoting vendor competition and significantly reducing in ‘vendor lock in’. Below is a breakdown of the key outcomes from study 1:

- There is currently unprecedented commercial investment in sensing technologies, rapidly improving sensing capabilities whilst driving down costs,
- Sensing technologies ***are*** COTS products,
- Automotive sensor fusion / general sensor fusion ***is not*** a COTS product.
- Sensing technologies whist similar in behaviour vary in implementation from supplier to supplier (e.g., power requirements and communication protocols used),
- A generic sensor fusion architecture that compiles with the GVA would be required to facilitate COTS sensing technologies integration,
- Multiple sensing technologies would likely be required to realise the full benefits of any sensor fusion implementation,
- The initial development of a generic sensor fusion architecture that is compatible with the GVA would likely be costly, however, the long term through life benefits would likely, considerably offset the initial investment,
- Commercial sensing g technologies would require further research for cost effective methods of ruggedisation to prolong life span.

It is clear that a collection of commercial sensing technologies could provide a highly detailed view of the local surroundings around MCC. The potential to greatly enhance situational awareness coupled with the cost effectiveness of commercial automotive sensing technologies is clear from this initial study. However, security, ruggedisation and the development of a generic sensor fusion architecture compatible with the GVA would likely be required to realise these benefits.

The following section presents a detailed analysis of automotive safety sub-systems (ADAS technologies) which provide an end-to-end package of functionality that can operate without the requirement of a sensor fusion architecture to be implemented, utilising a ‘bolt on’ approach.

4.3 Study 2 – Analysis of Key Automotive ADAS Technologies

As stated within previous chapters, during the last few years, the automotive industry has invested significant resources into improving the safety and comfort of passenger vehicles. Initially, systems with low levels of automation (e.g., forward collision warning) were used to assist the driver in avoiding collisions. As technology matures and the confidence levels increase, these systems are developed with increasing levels of automation (e.g., autonomous emergency braking, forward collision avoidance, lane keeping, etc.). The technology is being refined and improved rapidly with the vision of having fully autonomous vehicles available in the next 5 to 10 years [38].

Collectively, these technologies are commonly referred to as advanced driver assistance systems (ADAS). Different types of ADAS can be categorised based on the level of autonomy. For example:

- Lower level of autonomy: forward collision warning, blind spot detection, lane departure warning and parking assist.
- Higher level of autonomy: autonomous emergency braking, adaptive cruise control, forward collision avoidance and autonomous parking.

This analysis uses three suppliers, namely, Delphi, Continental, and Bosch. All three offer the same sub-system capabilities but with their own implementation. This provides a broad overview of not only the technologies but also the capability variation between suppliers that should be taken into consideration when considering procurement.

4.3.1 General Example Architecture for COTS Automotive Safety Sub-System Example

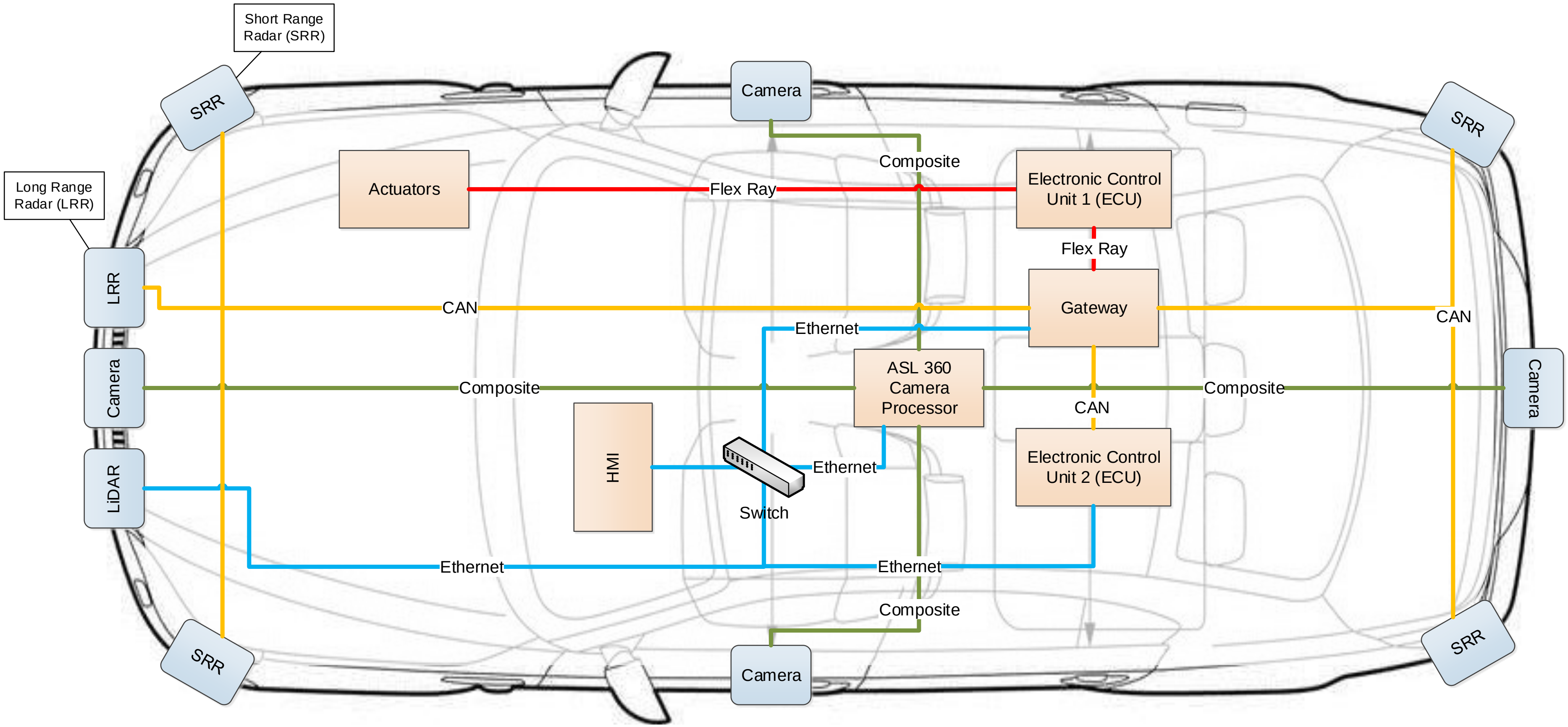

Figure 4.2 General automotive COTS safety sub-system architecture example [85]

4.3.2 General Automotive COTS Example Architecture Breakdown

The protocols shown in the diagram above (Figure 4.2) are examples of those used in different types of networks (i.e. safety critical, deterministic and best effort) that are likely to be required if many or all of the technologies presented within sub-section 3.4 Review of Automotive Bus Technologies were utilised for capability exploitation within a MCS. A brief description of these network types is provided within Table 4.8 below:

Table 4.8 High level description of network types shown within Figure 4.2

Network Type	Description
Safety critical bus: FlexRay used as an example of this type of network in Figure 4.2.	Safety critical network protocols are requirements driven. Providing not only determinism but also forms of fault tolerance/graceful degradation based on the requirements of the system or use case. Autonomous Emergency Braking (AEB) for example, would likely require a safety critical network protocol to communicate with the vehicles actuators to apply braking force in an emergency where crew/civilian life or the platform/mission could be at stake.
Deterministic bus: Controller Area Network (CAN) used as an example of this type of network in Figure 4.2.	Deterministic protocols provide a strict guarantee that message transfer will be completed in a predetermined (during system design) time frame. For instance, a data message from the Long-Range Radar (LRR) will always reach the gateway within 5 milliseconds.
Best effort: Ethernet, Composite, used as examples of these types of networks in Figure 4.2.	Best effort network protocols offer no guarantee for delivery or time of delivery. However, in the example above Figure 4.2, the LiDAR unit connected to the Ethernet uses TCP/IP which allows for the retransmission of data packets if the packets were lost and guarantees correct data packet order.

In this representative example, a combination of long-range radar (LRR), short range radar (SRR), LiDAR and camera sensors are used. The outputs of multiple sensors are fed into a processing module. The processing module analyses and fuses the data from the sensors and performs further identification and tracking of objects. The processing module connects to the vehicle backbone network (commonly CAN or Ethernet) and acts as a gateway to the subset of sensors connected to it. Since the sensors typically generate large data, the processing module assimilates the sensors' data and only sends useful information over the network as needed to avoid flooding the backbone network.

Information from the various processing modules is collated and fused together at the sensor fusion module to provide a complete, accurate and reliable understanding of vehicle surroundings.

The paragraph above describes an example of modern automotive ADAS capability. However, the exact details of the sensor fusion (how and at which stage the algorithms are executed) differs between manufacturers as the sensor fusion algorithms are proprietarily developed between major manufacturers (OEMs) and Tier 1 suppliers.

The following sections provide the critical argument against utilising end to end automotive safety sub-systems within military vetronics and present a selection of safety sub-systems in detail. The criteria for the term ‘most appropriate’ is based on the capabilities provided and how they could be utilised within a military land platform to provide increased platform safety through enhanced situational awareness. These safety sub-systems consist of the sensing technologies coupled with an Electronic Control Unit (ECU) containing all necessary algorithms provided by the supplier. These sub-systems whilst categorised as safety sub-systems by the suppliers, by no means infers that they use safety critical protocols or standards throughout their implementation.

Figure 4.2 describes the general architecture of automotive COTS safety sub-systems. Immediate integration problems are the mounting of sensing technologies and the communication buses/cabling required. Once solved, further problems are the technical integration into the GVA (data modelling etc.). Solutions to these and further requirements are explored and demonstrated using the testbed platform presented in Chapter 7 Generic Sensor Fusion Electronic Architecture Testbed.

Additionally, this testbed will also be the basis for exploring and designing an initial sensor fusion architecture showing a selection of the capabilities that can be achieved utilising basic sensing technologies (as found within various automotive COTS products).

4.3.3 Autonomous Emergency Braking Safety Sub-systems

This safety sub-system is designed to detect forward ego speed whilst identifying and tracking objects within the vehicles path, with the purpose of applying a certain amount of braking force in the event of a detected imminent collision (if speed is not reduced). At lower speeds (30 mph) the system can be configured to first warn the user of an imminent collision and if no response is detected from the user, then braking is applied to prevent a collision. At higher speeds where a collision is physically unavoidable braking strategies would be applied by the system to minimise collateral damage without operator intervention.

These strategies can range from braking assist where the sub-system will apply up to 50% braking power whilst alerting the user to the imminent threat of collision, or full autonomous braking (up to 100% braking force) to allow the vehicle to come to a complete stop.

Each of the reviewed suppliers' implementations have subtle differences but all follow the same techniques and approaches. They all allow for configuration of certain parameters after installation, please see Table 4.9 below for configuration parameter examples.

Table 4.9 OEM AEB safety sub-system configuration parameters

AEB system area	Description

Sensors	• Different sensor configurations allowing for higher vehicle speed emergency braking solutions, using a combination of sensors, for example:
	  ○ Light Detection And Ranging (LiDAR),
	  ○ Short range radar (0-50 metres wide field of view),
	  ○ Camera,
	  ○ Long range radar (0-250 metres narrow field of view).

Braking	• Maximum amount of braking force that can be applied autonomously, • Timing and distances for braking forces to be applied.

HMI	• Types of alerts to be presented to the user:
	  ○ Visual,
	  ○ Auditory.

Below is a description of the three selected suppliers AEB solutions currently available, detailing the slight variations of components/configurations they offer:

Delphi's implementation: is described as a collision mitigation system [86]. This system uses both a radar and camera system to identify/track objects and respond accordingly in the event of an expected collision,

Continental's implementation: is described as an emergency brake assist [87] utilises Continentals' Multi-function camera lidar unit (MFL) and depending on choice/configuration short range radar and/or long range radar,

Bosch: Bosch supply a system they present as a predictive emergency braking system [88], utilising (dependant on system configuration) short range radar, long range radar, stereo video camera and/or normal camera systems.

Figure 4.3 on the following page describes the operational behaviour of a generic AEB safety sub-system in four phases. It should be noted that these phases are simply an example of typical AEB operation, and these could be configured to suit the use case / application.

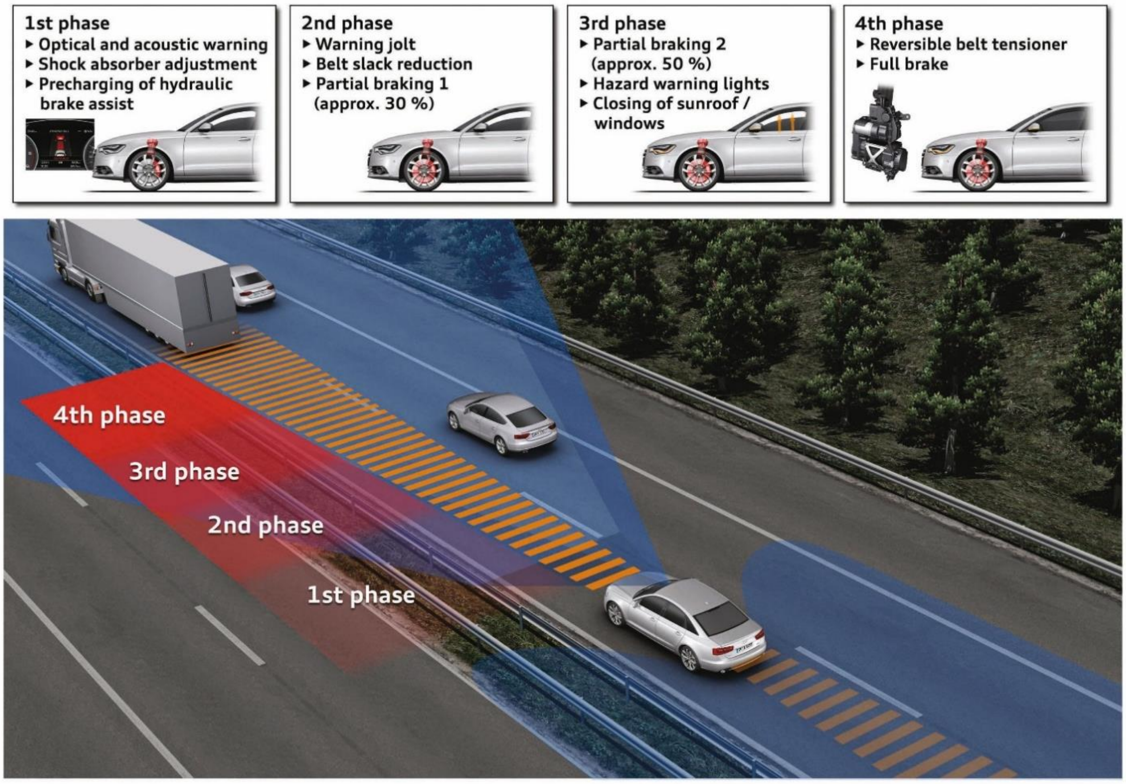

Figure 4.3 Example of emergency brake assist safety sub-system behaviour [89]

Below (Table 4.10) is a description of the four phases shown in Figure 4.3.

Table 4.10 Automatic Emergency Braking (AEB) safety sub system phases

Phase event activation	Description of activated events
Phase 1	• Warning alerts are presented to the driver of the vehicle, either visual or auditory or both, • Preparation of suspension system in anticipation of the rapid application of braking force, • Preparation of braking actuator system in anticipation of the rapid application of braking force.
Phase 2	• Physical jolting of the vehicle provides another warning to the driver as the vehicle begins declaration (an additional alert), • Other actuators activate for enhanced safety (in this case the vehicles' seat belts tighten and reduce any slack in the belt), • Braking force begins to be applied after the initial jolt to a maximum of 30%.
Phase 3	• Braking force increases to 50% of total maximum, • Further activation of other safety related actuators (in this case hazard warning lights are turned on to warn vehicles and windows/sunroofs close)
Phase 4	• Full braking is applied to bring the vehicle to a stop.

Table 4.11 below details the SWOT analysis for AEB safety sub-system technologies exploitation within a MCS.

Table 4.11 SWOT analysis of collision mitigation technologies exploitation in a MCS

<table>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td>

Capability to autonomously reduce the effects of (or prevent) a forward collision,
Requires no software development for intended application,
Suppliers offer semi-tailored solutions to create sub-systems that are fit for purpose, examples of configuration options would be:

Stopping distances,
Amount of braking force to be autonomously applied,
Types and timings for warnings/alerts to users when collision is expected/detected to be imminent.

</td><td>

Would be difficult to extend capabilities beyond its intended use,
Would require integration into brake system and actuators across the platform’s automotive sub-system using a safety critical protocol and may require recertification,
Would require extensive configuration,

At a minimum, it is likely that each vehicle type/variation would require its own specific configuration,

Would require testing after installation, the cost of which would need to be assessed before procurement.

</td></tr>
<tr><th>Opportunities</th><th>Threats</th></tr>
<tr><td>

Potential to utilise this technology as part of a remote vehicle recovery use case, for example,

Preventing collisions if vehicle being remote controlled by a lead vehicle operator or if the recovered vehicle is in platooning mode of operation (following vehicle in front semi-autonomously,

Re-utilisation of sensing technologies for other purposes by other GVA sub-systems if used with DDS by being integrated with a GVA adaptor and compatible Data Model,
Could provide part of the initial basis for convoy/vehicle platooning (vehicle autonomously following one another).

</td><td>

ECU and software are proprietary, creating a vendor lock-in for upgrades or maintenance,
Reliance on sensing technologies for correct operation[2],
Increases vehicle threat signature/signal emissions when in use due to the use of radar/LiDAR,
The system may not gracefully degrade in the appropriate manner given the difference of the intended usage (the system is more likely to suffer damage given the operating environment),
Legacy vehicles that are still operational may not have the required actuators or infrastructure to support emergency braking integration.

</td></tr>
</table>

Exploitation Use Cases

Two use cases have been defined for this technology and are presented within Chapter 5. The first (Emergency Braking Sub-system – Use Case 1) describes the potential benefits of exploiting AEB technology to protect not only the vehicle but also civilians and civilian/military infrastructure. This use case highlights the potential benefit to vehicle convoys when under fire.

The second use case (Emergency Braking Sub-system – Use Case 2) presents how the technology could help to protect not only the vehicles and crews but also civilians who happen to be around the vehicle whilst the vehicles are operating within a cluttered urban environment.

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[2] Includes risks such as: LiDAR spoofing or sensor damage.

Preliminary Integration Assessment

The integration of AEB systems is challenging due to requiring tightly coupled integration into braking system/actuators. To create a loosely coupled approach (supporting modularity) would require integration into the GVA. However, as GVA in its current state is not safety certified, integration would require safety certification if data exchange (back and forth) took place between the AEB sub-systems and other MCS sub-systems across DDS. For example, if the AEB sub-system activates based on threats identified through Defensive Aid Suite (DAS) and vice versa. This would increase integration time and costs.

However, if the GVA coupled sub-systems only use the data produced by the AEB sub-system to fuse it with other military sensors (e.g. only one-way communication: AEB to GVA environment, sensor fusion for new military applications) then it would not require safety certification. This approach only requires the development of a GVA adaptor with the GVA data model and DDS for use with the AEB sub-system.

Additionally, system behavioural configuration parameters would need to be considered carefully given the context, in some cases a MCS could feasibly want to ‘keep going’ as it were, even if there is an obstruction (i.e. an ambush/road block whilst under small arms fire).

4.3.4 Parking Assist Systems

The parking assist technologies contain a set of sensors, an ECU and either an output for an HMI/auditory alarm or a selection of pre-built HMI(s) requiring mounting and installation. These safety sub-systems provide either visual or audible feedback or both to the user with the aim of aiding reversing manoeuvres whilst in the driving position.

There is significant variation between suppliers for this type of system, although they all utilise similar sets of sensors and configurations they differ in their application. Delphi offer a parking assist system which provides visual assistance to the user via the included HMI highlighting current trajectory and desired trajectory through a camera feed with a graphical augmented reality style overlay as shown in Figure 4.4.

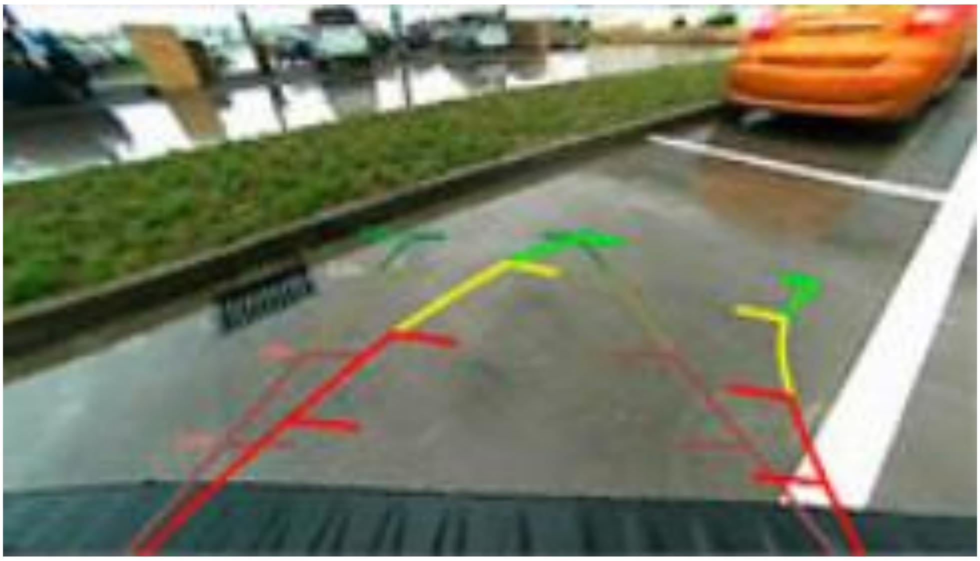


Figure 4.4 Delphi augmented parking assist display [90]

Continental utilise a surround view vision system shown within Figure 4.5 below. This provides the user with a top-down surround view of the vehicle while the parking manoeuvre is being completed. The vehicle is overlaid on the 360-stitched image view in an augmented reality style and displayed on an HMI. This sub-system is supplied with a set of four cameras mounted on the exterior of the vehicle and an ECU with proprietary camera stream stitching software. However, it is also possible to utilise additional sensors such as radar, LiDAR to increase accuracy and performance of the system.

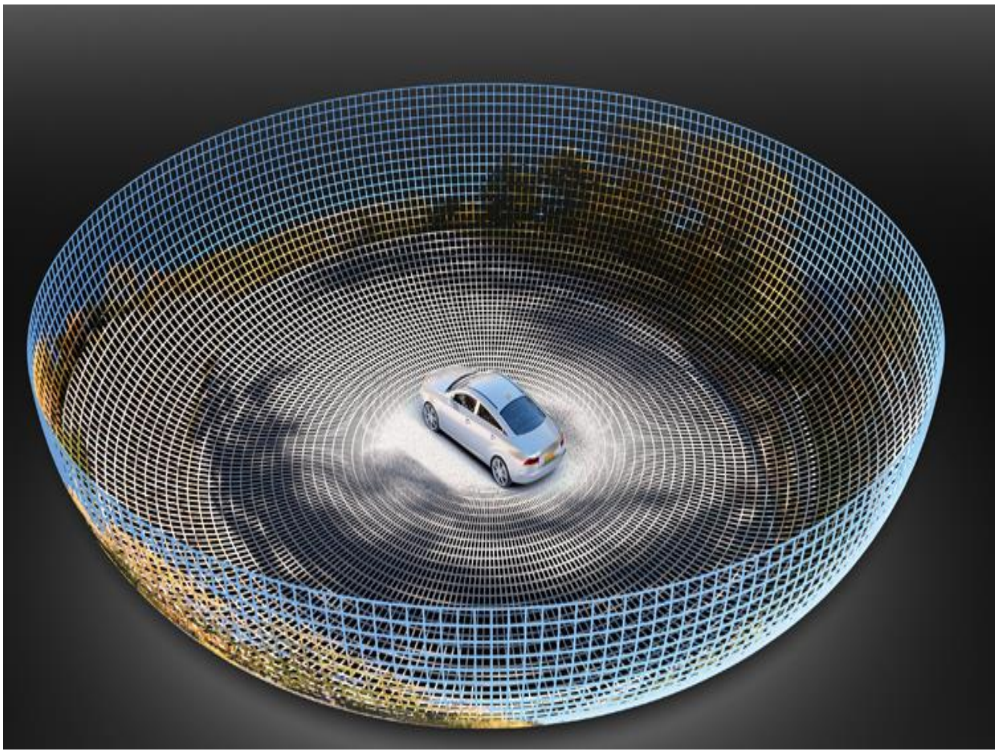


Figure 4.5 Continental surround view 3D bowl [91]

This system also provides the ability to configure or reconfigure the components (e.g. cameras/additional sensors) and by applying different algorithms developed and supplied by continental. It is expected that these functions would require additional sensing technologies such as LiDAR and Radar. Continental offer functionality such as:

- **Autonomous parking** – Displays available spaces within the vehicle's local area, after the user has selected a space via the HMI the car will then proceed to park in the selected space.
- **Autonomous parking (trained)** – Allows the user to perform a set of manoeuvres and park the vehicle once (training), which the system can then use to fully autonomously complete the same manoeuvre (in the same space) using the surround view system to navigate in real time. It is implied but not confirmed that the vehicle could operate within a dynamic (react to a changing) environment using this software.
- **Remote parking** – Allows the user to park the vehicle using software whilst in or outside the vehicle. The current software application can be used on a mobile device (similar to an application that one would run on a smart phone for instance).

The specifics of these technologies are currently unclear as is their Technology Readiness Level (TRL). These attributes would need to be assessed in the future.

Bosch offers a similar approach to Continental; however, it appears that their software technologies are of a low TRL in comparison to what Continental present. Bosch discusses systems with connected parking assist, where the vehicle communicates with a networked service (The Internet) to locate parking positions within car parks etc. The infrastructure for such operations isn't currently fully implemented or available. Therefore, it is considered a near future technology.

Table 4.12 presents the SWOT analysis for exploiting parking assist systems within military vetronics.

Table 4.12 SWOT analysis of parking assist technologies exploitation in a MCS

Strengths	Weaknesses

• Depending on supplier, sub-system software can be configurable,
  ○ Continental and Bosch for example offer a wide range of software configuration options (such as: remote parking etc.),
• Some systems have the potential to provide safe, short distance or low speed vehicle manoeuvring whilst under armour,
  ○ It is feasible that the system could be used whilst the crew are under armour to manoeuvre to a safe position (if encountering small arms fire in a street for example).
	• Would likely require considerable configuration and testing,
	• It is not clear at which Technology Readiness Level (TRL) Continental's or Bosch's remote parking functions are,
	• Would likely require extra crew/operator training,
	• As with AEB safety sub-systems any autonomous behaviour or remote operations would require integration into many of the vehicle's actuators and control systems developed by separate vendors.

Opportunities	**Threats**
• Remote parking functionality could feasibly be useful for many military applications, such as: remote vehicle recovery allowing a remote operator to manoeuvre the vehicle to an attachment point on another vehicle whilst remaining under armour, • Re-utilisation of sensing technologies for other purposes by other GVA sub-systems if used with DDS by being integrated with a GVA adaptor and compatible Data Model.	• ECU and software are proprietary, creating a vendor lock-in for upgrades or maintenance, • Possible damage to sensors during theatre operations compromising system performance, • Could have limited operational capability during night-time if the system is primarily camera based.

Exploitation Use Case

The third use case shown within Chapter 5, Parking Assist Sub-system – Use Case 3, presents an example of exploitation for parking assist safety sub-systems within military land platforms allowing a single crew member to safely manoeuvre the vehicle (within a base of operations, for example). The fourth use case described within Chapter 5, Alternative Parking Assist Sub-system – Use Case 4 presents a potential exploitation of trained autonomous parking technology to aid manoeuvres in a Degraded Visual Environment (DVE). It is expected to be a near future technology for the automotive industry.

Preliminary Integration Assessment

It is expected for use case 3 (Parking Assist Sub-system – Use Case 3) integration requirements would be reduced due to the system being mostly self-contained. The system would require configuration for each vehicle it was to be installed onto (camera mounting, and software configuration setup based on mounting positions) along with power requirements for each camera and the ECU. However, the output could be routed to an existing HMI (rather than using the included HMI) within the vehicle, further reducing integration effort (if a compatible HMI was available).

The system also has the potential for enhancing situational awareness in theatre of operations by providing a surround view of the vehicle local vicinity whilst the crew remain under armour.

However, for use case 4 (Alternative Parking Assist Sub-system – Use Case 4) whilst feasible, it is also likely to be considered a near future exploitation example. This sub-system has similar integration requirements as AEB integration (discussed within section 4.3.3). Although the behaviour and operation would be safety certified under ISO 26262 (if used for the intended application) due to the unintended operation it is likely that significant further testing and certification would be required (also described in section 4.3.3 Preliminary Integration Assessment).

This would increase the cost of such an exploitation example, it is likely that crews would require basic training to understand and operate the system. The system could feasibly perform its functions autonomously; however, it is expected that for the near future crews would activate the emergency manoeuvre in the event of a sudden DVE.

Alternative Parking Assist Systems with Ultrasonic Sensing Technologies

There are alternative surround sensing systems available costing around $200 per unit and manufactured by Chinese suppliers. These systems could be used to demonstrate surround object detection using cheap multiple sensors of the same type (a group of ultrasonic sensors for instance as shown in Figure 4.6).

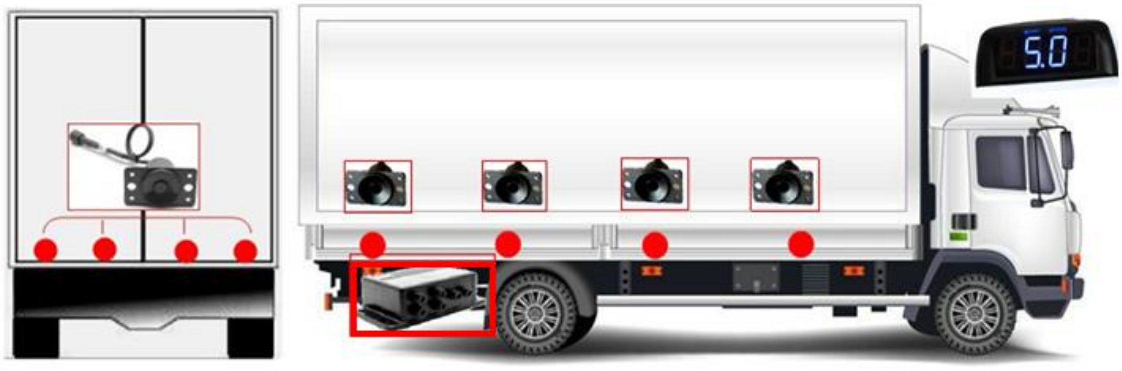


Figure 4.6 Cost effective alternative parking assist system (ultrasound sensors) [92]

Moreover, these systems could also be useful for integrators/researchers to explore simple problems (sensor mounting and cabling, power integration, data model integration etc.) and help to provide an understanding of the potential benefits of using automotive COTS sensing technologies.

The table shown below (Table 4.13) describes a brief SWOT analysis of alternative parking assist technologies based on ultrasound sensing technologies exploitation in MCS.

Table 4.13 SWOT analysis of alternative parking assist technologies exploitation in a MCS

Strengths	Weaknesses
• Offers enhanced situational awareness, • Simple to integrate into a vehicle requiring only mounting and power.	• System is unlikely to be robust and failure rates could possibly be high due to the very low cost of the system.
Opportunities	**Threats**
• Re-utilisation of sensing technologies for other purposes by other GVA sub-systems if used with DDS by being integrated with a GVA adaptor and compatible Data Model.	• Damage to sensors during theatre operations compromising system performance.

Exploitation Use Cases

This technology could provide rapid deployment for turning circle assistance applicable only to short or non-barrelled vehicles as described within Chapter 5, Alternative Parking Assist Sub-system – Use Case 4.

The sensing of object distances from the vehicle would provide audible and visual warnings/description to the operator during turning/rotational manoeuvres (tracked vehicles, on the spot turning for example).

The table within Alternative Parking Assist Sub-system – Use Case 5 presents a simple use case for this system that could be quickly integrated and utilised for around vehicle object detection enhancing crew situational awareness within a MCS (detection of people approaching the MCS for example).

Preliminary Integration Assessment

The ultrasound alternative parking assist technology is likely to require minimal integration effort. The sensors require mounting all around the vehicle to provide surround object detection. It would be considered a benefit to also collect the data produced and make it available in a visual presentation to further exploit this simple technology. This would increase integration effort and require an adapter/gateway (for data collection/transmission) and likely the development of simple Graphical User Interface (GUI) to display relevant data. Adding this type of modification could further enhance the use case described above (section 4.3.4 Exploitation Use Cases).

4.3.5 Rear Cross Traffic Alert

This safety sub-system provides the vehicle with a proximity/object detection warning using radar sensors mounted at 45° angles from the rear corners of a vehicle (feasibly the sensors could also be mounted on the front of the vehicles). The system can detect and alert the user to objects or movement within the vehicle's blind spots by using short range radar as shown within Figure 4.7 below.

All of the three OEM suppliers utilise a very similar approach for this type of safety sub-system, having a system of short/mid-range radar sensors with their own algorithm implementations. The detection ranges can vary between 0 to 50 metres depending on supplier; alerts to the user can be either auditory or visual or both.

Figure 4.7 Continental Rear Cross Traffic Alert (RCTA) sub-system example [93]

Table 4.14 below, describes the SWOT analysis for the utilisation of a rear cross traffic alert system within military vetronics.

Table 4.14 SWOT analysis of Rear Cross Traffic Alert technologies exploitation in MCS

Strengths	Weaknesses
• Utilises only a single sensor type which reduces integration effort, • Allows for rapid deployment of object detection capability, • Could be installed at the front as well as the rear of a vehicle for around corner early warning.	• Utilises only one type of sensor (short range radar) limiting capabilities, • Unlikely to be able to identify specific threats without additional sensing technologies (i.e. cameras).
Opportunities	**Threats**
• If used in conjunction with a vision system/camera mounted in the same location as the radar modules, threat identification and tracking could be achieved, • Re-utilisation of sensing technologies for other purposes by other GVA sub-systems if used with DDS by being integrated with a GVA adaptor and compatible Data Model.	• Increases vehicle threat signature/signal emissions when in use due to the use of radar.

Exploitation Use Cases

Use case 6 (Chapter 5, Rear Cross Traffic Alert Sub-system – Use Case 6) presents the exploitation of this technology for the mitigation of barrel strike and turret rotational assistance. Mounting the radar sensors in the four corners of a turret's base would allow for the detection of objects/obstructions within the barrel/turret turning circle. Objects could be tracked each side of the barrel to avoid barrel strike, whilst the two radar sensors mounted on the rear of the turret providing strike warnings/rotational assistance when rotating the turret whilst under armour.

Use case 7 shown within Chapter 5, Rear Cross Traffic Alert Sub-system – Use Case 7 highlights simple object detection utilising the system closely to its intended design purpose. Primarily this could be useful to assist with single crew manoeuvres capability within the base of operations.

Preliminary Integration Assessment

For use case 6 (Rear Cross Traffic Alert Sub-system – Use Case 6), integration would require mounting points for at least four radar sensors around the base of the turret (preferably each corner of the turret at 45° angles to the turret). The system would also require radar track data to be output to an HMI, likely requiring an adapter/gateway to transfer data from the sub-systems ECU to the HMI.

It is likely that for single crew vehicle manoeuvres (shown in Rear Cross Traffic Alert Sub-system – Use Case 7) integration effort would be minimal. This is due to the system having the least sensors (two to four radar units) and a single ECU, coupled with an output for a display or audible alarm. This is all that's required for the system to function.

However, for use case 8 (Chapter 5, Combined COTS Safety Sub-system – Use Case 8) integration and operation whilst feasible would be significantly more complex. The integration of a vision system mounted in the same location as the radar sensors coupled with another ECU to complete the fusion task along with a bespoke fusion algorithm for defined threat detection in the context of military operations is a significant integration challenge. This could be considered a near future goal for this type of combined COTS safety sub-system technology.

4.3.6 A Generic Mounted Close Combat COTS Integration Architecture Example

The diagram presented on page 106, Figure 4.8, shows the hypothetical Future Ground Combat System (FGCS). This is a companion diagram to the general automotive architecture example shown previously (Figure 4.2). The diagram shows a theoretical example of how a selection of the reviewed technologies (along with communication network type examples) could be integrated within a military land platform.

Table 4.15 on the following page provides details of the COTS technologies (name of the technology and functionality, cross referenced with the applicable use case) contained within Figure 4.8 General FGCS COTS integration architecture example, page 106.

Table 4.15 Description of COTS technologies, functionality and use cases described within Figure 4.8

COTS Technology	Functionality and Use Case
Autonomous Emergency Braking (AEB) safety sub-system	• Providing active safety to avoid collisions between vehicles whilst in a convoy (Chapter 5, Emergency Braking Sub-system – Use Case 1), • Providing increased civilian/civilian infrastructure safety when operating vehicles within a cluttered urban environment (Chapter 5, Emergency Braking Sub-system – Use Case 2).
Parking Assist (PA) (camera driven) safety sub-system	• Providing single crew manoeuvring capabilities whilst under armour (Chapter 5, Parking Assist Sub-system – Use Case 3).
Rear Cross Traffic Alert (RCTA) safety sub-system	• Providing barrel strike early warning (Chapter 5, Rear Cross Traffic Alert Sub-system – Use Case 7), • Providing turret rotational assistance (use case 7 as above), • Providing around corner viewing (combined with camera system) for threat identification and early warning (Chapter 5, Combined COTS Safety Sub-system – Use Case 9).

Combined Technologies Exploitation Use Cases

Based on the diagram shown in Figure 4.8, a selection of use cases has been developed utilising a combination of the technologies reviewed.

The combined use case shown within Chapter 5, Combined COTS Safety Sub-system – Use Case 8, describes a more complex but feasible exploitation of Rear Cross Traffic Alert technology for round corner presentation/viewing by coupling a vision system (parking assist technologies) capable of threat identification triggered by the object detection of the rear cross traffic alert safety sub-system.

The final combined use case Chapter 5, Combined COTS Safety Sub-system – Use Case 9 describes how any combination of integrated COTS safety sub-systems could be used to enhance MCS crews' situational awareness (crowd monitoring/threat detection etc.).

Preliminary Integration Assessment

Additional integration effort (algorithm development) would be required to enable the capabilities described within the use cases above. Each COTS safety sub-system would need to be attached to GVA adapter/gateway (for data availability). This would support GVA compatibility whilst also providing data across the DDS middleware to other vehicle sub-systems. This data transfer is necessary as the functionality required for these use cases will need additional algorithm/processing development to make use of the safety sub-systems data outputs, this would in turn increase safety sub-system integration costs and effort.

General FGCS COTS Integration Architecture Example

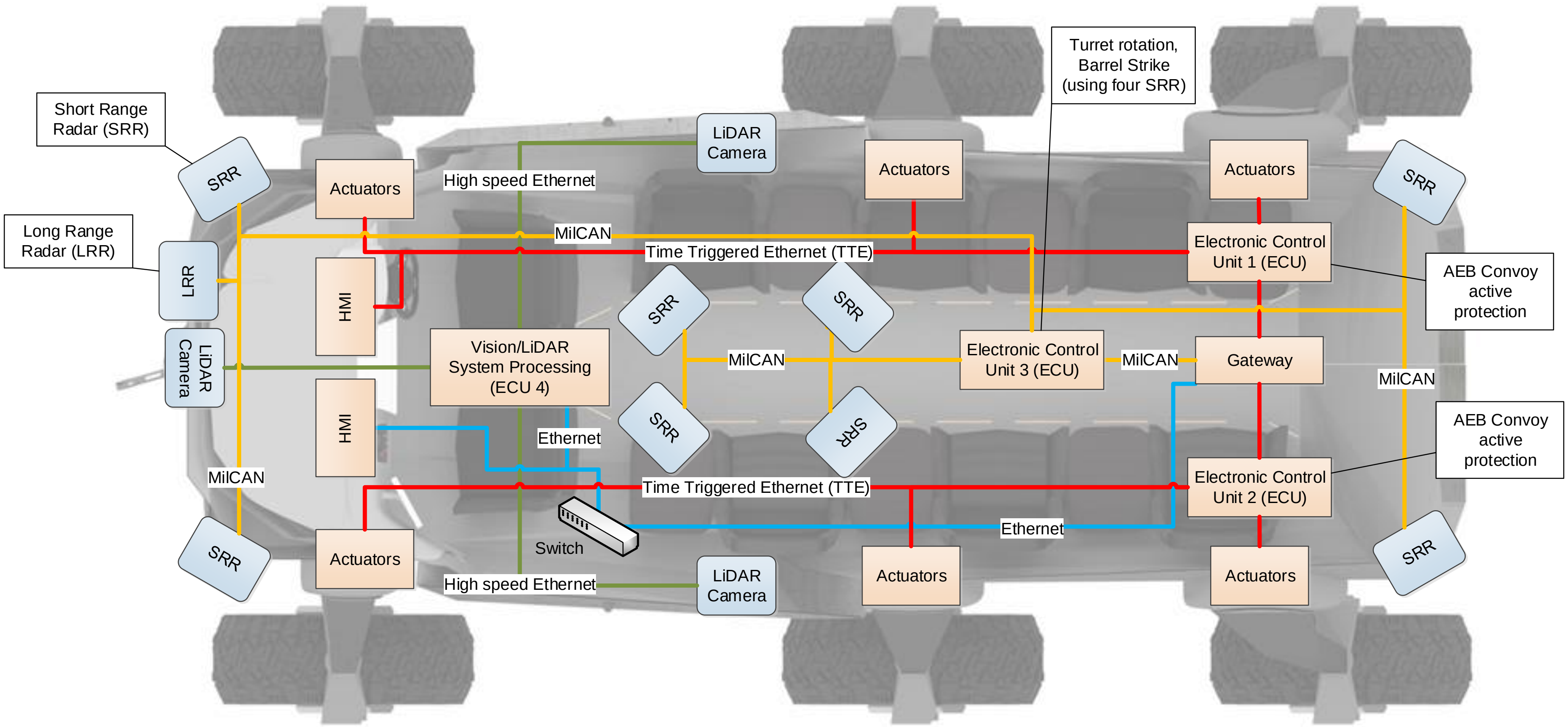


Figure 4.8 General FGCS COTS integration architecture example

4.3.7 Summary of Study 2

The results of this work conclude that utilising commercial automotive safety sub-system technologies (ADAS proprietary sub-systems) within military land platforms can provide enhanced safety for crews, civilians and civilian / military infrastructure. However, a notable constraint for the utilisation of COTS safety technologies within MCS is the reliance on OEM supplier (vendor lock in) for the proprietary components of the system (such as software/software upgrades and hardware/hardware upgrades, for example). Additionally, the automotive COTS safety sub-systems presented within this study offer limited room for modification beyond intended usage.

4.4 Conclusion

The following sections present the final conclusions for the studies completed within this chapter.

4.4.1 Study 1 – Commercial Sensing technologies

In summary, commercial sensing technologies demonstrate clear benefits in addressing the safety and situational awareness challenges that often confront mounted combat vehicles in complex urban environments.

The potential capabilities are numerous (described in further detail within Chapter 5, 5.2.2 Fusion Process Examples). However, the deployment of these capabilities will be constrained by available platform resources (computational cost, power, size, weight etc.). The overall system design would also likely have an impact on available selection of capabilities, e.g. different land platforms will have different power availability, networking and processing capabilities and available mount points for sensors etc.

Additionally, a common disadvantage shared by commercial sensing technologies (from a security perspective) would be publicly available information on many commercial technologies, e.g., data sheets, communication protocols etc. which could enable an attacker to understand system operation and exploit it to cause disruption. Therefore, careful considerations must be paid to security. i.e., utilisation of message encryption and or node authentication (e.g., DDS Security Specification Version 1.0 [94]).

4.4.2 Study 2 – ADAS safety sub-systems

Feasibly the sub-systems analysed can be utilised as standalone end to end sub-systems without using DDS as a middleware for communication. However, it is expected that for MCS to obtain the full benefits of COTS automotive technologies or COTS sensing technologies, a Sensor Fusion Architecture (SFA) is required that can be integrated within the GVA environment/approach. A resilient SFA would be required to operate in military environments with ruggedized COTS systems to endure the operating conditions and expected duty-cycles. This can provide enhanced capabilities that these standalone, end to end ADAS sub-systems cannot offer.

To complement the SWOT analysis completed for each individual selected technology discussed within Study 2 – Analysis of Key Automotive ADAS Technologies, a high-level SWOT analysis is presented below (Table 4.16) to describe the use of automotive COTS safety sub-systems within military land platforms.

Table 4.16 High level SWOT analysis for the integration of COTS automotive safety technology sub systems within military land platforms

Strengths	Weaknesses
• COTS automotive safety sub-systems can provide enhancements to safety functionality for MCS, • Many automotive COTS safety sub-systems also have the potential to: o Enhance situational awareness, o Reduce crew cognitive burden, o Improvement of reaction times in rapidly evolving events (system or human). • Costs of these systems are market driven and have a mature international supplier base, • Multiple safety functions can be implemented on a single specialised ECU, o Potential to reduce integration requirements (Size, Weight and Power (SWaP)). • Suppliers such as Continental, Bosch etc. conform to national and international safety standards for automotive technologies (hardware and software). o Supplier has certification to meet safety requirements such as AUTOSAR and ASIL (ISO 26262) further reduces overall costs of having to perform costly verification and validation on each individual component.	• Limited flexibility beyond exploited capability or intended supplier functionality, • All presented COTS sub-systems are unlikely to be ruggedised to military standards or specifications, • To utilise any autonomous functionality provided by automotive COTS safety sub-systems would require integration into existing safety critical sub-systems (for example operation of AEB with X-by-wire, • These systems likely do not use open standards and interfaces throughout their design, • Requires modification and increased cost to support GVA interfaces, • COTS automotive sub-systems are not designed with modularity in mind, • Do not provide HUMS information/interface.
Opportunities	**Threats**
• The ability to take advantage of significant commercial investment in new sensing technologies, ECUs and complex software solutions, o This point is considered one of the most significant opportunities for the utilisation of COTS technologies in general. The leverage provided by offering OEM suppliers a new market coupled with the fierce competition between OEMs maximising savings for the UK MOD procurement agency. • Potential for rapid deployment supporting Urgent Operational Requirements UOR, • Potential to avoid/reduce collateral damage, • It is also feasible to use the sensors procured with these safety sub-systems within a GVA compliant sensor fusion architecture if one becomes available in the future (i.e. Ministry of Defence (MOD) developed GVA compliant sensor fusion architecture).	• Safety and security specifications would require careful consideration and close communication with supplier, • Integrating automotive COTS safety sub-systems and sensing technologies increases cyber security threat vectors, • Many proprietary software/hardware components, this could prevent possible future re-use, therefore reducing overall value of procurement, • COTS supplier base business model may not support or address the requirements of defence equipment procurement and support, • If upgradability were available for a COTS sub-system (software or hardware) this will likely be vendor locked, i.e. improved performance sensors (solid state LiDAR for example); • Reliance on supplier for software modifications and bug fixes, updates etc.

A notable constraint for the utilisation of COTS, ADAS, safety technologies within MCS is the reliance on OEM supplier (vendor lock in) for the proprietary components of the system (such as software/software upgrades and hardware / hardware upgrades, for example). Additionally, the automotive COTS safety sub-systems presented within this body of work offer limited room for modification beyond intended usage. A summary is provided below:

- The standalone COTS safety sub-systems investigated can offer rapid deployment of specific safety features to enhance safety within MCS in many different scenarios/use cases, meeting UOR,
- Safety certification (ASIL within ISO 26262) on many of the technologies (hardware and software) presented within section 4.3 Study 2 – Analysis of Key Automotive ADAS Technologies have already been completed by the supplier. This is considered a benefit due to hardware and software verification and validation being complicated, time consuming and costly,
- Many of the technologies could be exploited to offer basic situational awareness gains, such as: robust object detection (people or vehicles approaching the MCS),
- The COTS safety sub-systems presented in section 4.3 Study 2 – Analysis of Key Automotive ADAS Technologies are likely to require additional ruggedisation before / during installation to meet military standards / specifications, especially the sensing technologies mounted on or around the vehicle. COTS sub-systems require modifications to support GVA interfaces, incurring further cost but increasing exploitation opportunities.

To fully support COTS sensing technologies within the GVA environment modifications/additions to the current GVA Land Data Model (LDM) would likely be required. The testbed demonstrator (presented within Chapter 7) can be utilised to assess the integration of COTS automotive safety technologies within a GVA environment and highlight a selection of the capabilities discussed in Chapter 5 Commercial Technology Integration Levels (CTIL). The testbed could also be used for the cost-effective exploration for securing COTS technologies when integrating them into GVA.

4.4.3 Analysis of COTS integration for GVA Military Land platforms

Since the late 1990s defence procurement agencies have identified the increasing need for the adoption of COTS technologies, be that software or hardware [95]. However, military doctrine and past procurement practice has slowed or prevented the adoption of commercial technologies integration into military land platforms [9]. Given that it is clear a drive towards COTS integration within military vetronics is rapidly becoming a reality as discussed within Chapter 1. The following chapter presents the research carried out to aid understanding of the technical and more importantly the non-technical integration requirements necessary to support COTS integration within military land platforms.

5 Commercial Technology Integration Levels (CTIL)

5.1 Introduction

The selection and procurement of technologies to be used within military land platforms can be a lengthy, complicated process [9]. With current military doctrine changing as discussed within Chapter 1, potentially an approach is required to support the procurement process of COTS technologies. To help facilitate the selection and integration of COTS technologies into military vetronic architectures this research proposes a framework for assessing not only the ease of integration but more over the exploitation possibilities of any given technology. The Commercial Technology Integration Level (CTIL) framework presented within this chapter is designed to provide an assessment for the integration requirements of any given technology.

The initial use cases developed within Chapter 4 COTS Sensing Technologies Within Mounted Combat Systems, provide numerous exploitation opportunities for commercial automotive sensors or technologies in military land systems. However, commercial technologies can differ broadly in relation to how integration can be achieved within a vetronics platform. On one end of the spectrum, there are systems that are designed to be fully integrated with other automotive systems and use communication / interface protocols commonly used in the automotive industry. On the other end of the spectrum, there are systems that are designed to be self-contained providing the complete capability, often with priority communications or software interfaces.

There are also two approaches to integration to achieve capability: the first approach is to use the technology for its intended application, the second approach is to exploit the technology beyond its intended application to provide further capability relevant to the military context. The first approach has the benefits that a technology applied in such a manner exhibits an operation that is well understood and documented. The second approach requires engineering effort to identify the potential and assess the performance of the technology in the desired military application.

Therefore, in order to effectively exploit commercial and automotive technologies there is a need for a common and consistent approach to manage the selection and integration costs of these technologies when attempting to insert them into military vehicles. Part of such an approach is the definition of integration levels that help to determine the exploitability, costs estimate (time and financial) of any given COTS technologies.

The following sections present the basis for a COTS integration framework required for achieving a reduction in risk versus benefits of any given COTS technology.

5.2 Associated research

Considerable research has been carried out over the last 25-30 years regarding defence procurement strategies. There has been an increasing requirement over these years to further reduce costs and decrease the time taken to integrate a new technology into any given platform by delivering increased COTS technology within the supply chain [11, 95].

As discussed previously, the current and expected theatre of operations is within congested urban environments, the need to rapidly reconfigure military platforms to meet current / changing threats, potentially on a daily basis drive the requirement for rapid insertion of technologies to increase survivability in the asymmetric battlefield in a cost-effective manner. COTS technologies fit this requirement very well. As this is the case, one of the first steps towards a more effective and safe COTS insertion program would be a framework for the selection of a candid COTS technology [96-98].

Rapid COTS insertion, however, is obviously not a silver bullet to procurement. There are many challenges to overcome such as developing the COTS technologies further to be able to withstand some of the potentially harsh operating environments. Likely COTS technologies would need some form of research for cost effective ruggedisation (i.e. to withstand heat, dust and severe vibrations). However, this can also in some cases be mitigated by simply having ‘throw away’ COTS products. COTS products (dependent on costs when bought in volume) could be considered as replaceable as munitions for example.

5.2.1 Barriers to change

There does appear to be a barrier to the adoption of COTS technologies due to current doctrine within the MoD and the defence industry as a whole, almost a ‘this is how it is done’ that ultimately resists change [9]. However, this not completely unwarranted as decreasing time to insert new technologies into any military platform could potentially (and obviously) reduce survivability not only to the mission but of course to any crews operating the platform (derived from extensive meetings and conversations with the UK MoD personnel).

Whilst the above is valid there is evidence that when COTS insertion is done correctly the survivability for crew and mission can be increased and done so cost effectively.

5.2.2 Fusion Process Examples

Below is a selection of high-level sensor fusion exploitation potential for various sensing technologies with some real-life examples of such technologies which were developed within the VRC research lab (i.e. the Kinect depth sensing example, page 114). These high-level exploitation examples (along with the research presented within Chapter 4) were then developed in conjunction with the UK MoD to detailed, structured use cases (presented further in this chapter). Table 5.1 below describes these high-level fusion process examples.

Table 5.1 High-level fusion process exploitation examples

High level exploitation categories	Description
Navigational aids (emergency route planning)	Using LiDAR based technologies to create a 3D map in conjunction with odometry data/camera systems to navigate in the absence of navigational systems/GPS (as shown in Figure 5.2 Kinect distance measurement).
Landmine/IED detection aids	Using LiDAR/Radar based technologies to provide a detailed 3D map of the terrain. This can then be used during a second observation as a comparator indicating recent changes to terrain that match specific traits of landmine/IED insertion using pattern matching.
Proximity detection	Proximity detection for manoeuvring vehicles or for persons approaching the vehicle using mounted ultrasonic parking sensors (0.5m-5m range), providing simple alarm feedback if objects are detected within a specific range. Can also be achieved using 360° surround view camera system.
Threat detection (facial recognition, pattern analysis, object tracking)	Providing the capability of alerting the crew of known adversaries using facial recognition technologies with pattern matching and object tracking. (Camera system, LiDAR, Radar).

Not only is it useful to perform basic fusion for object classification at the sensor level but tis also provides utility to the wider IOBT (Internet Of Battlefield Things) BMS (Battle Management System.

The following section further details these capabilities and their exploitation within the context of an MCS.

Sensor Data Manipulation and Fusion Example

An open-source algorithm that fuses the video from the Kinect RGB camera with the depth stream data from the Kinect depth sensor is implemented to create a live textured 3D view of the environment, which can be tilted, rotated and zoomed in real-time. A screenshot of this 3D view can be seen in Figure 5.1.

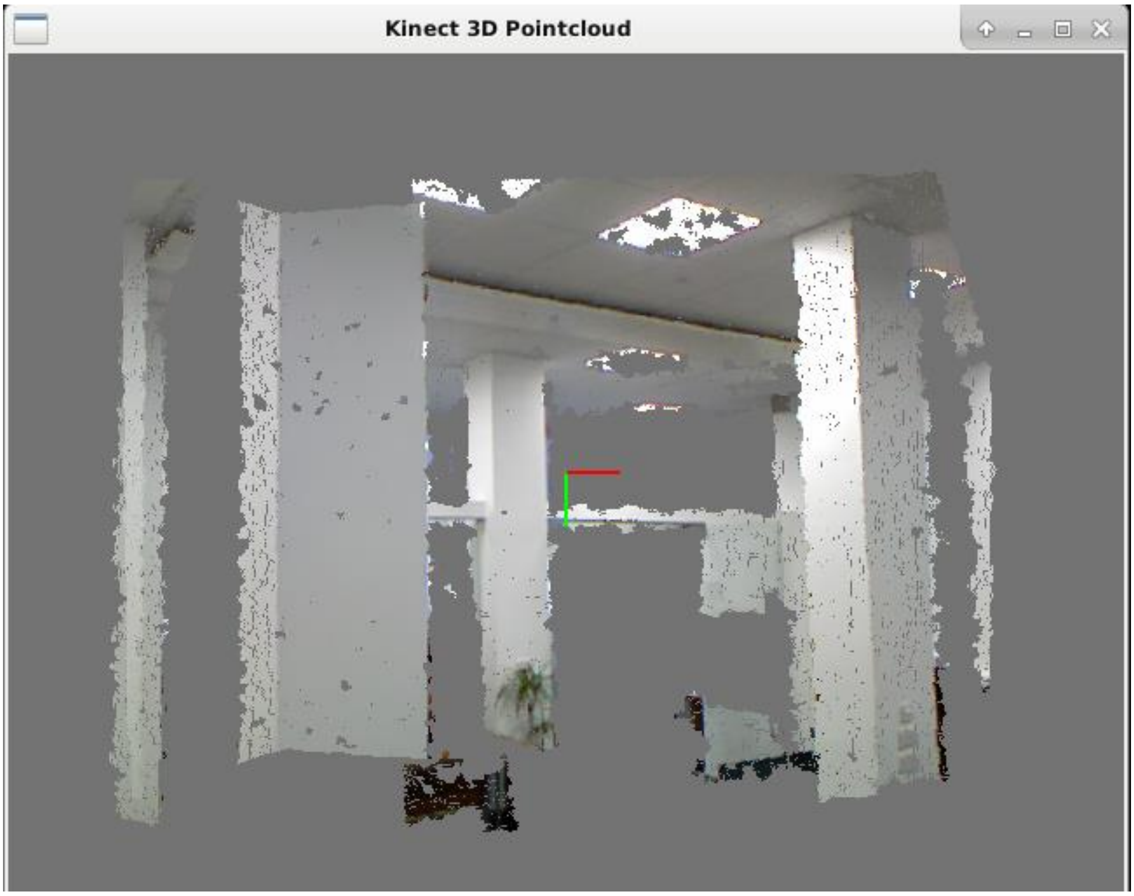


Figure 5.1 Kinect textured 3D view

Another application implemented uses the Kinect depth data to measure the distance between any two points in 3D space. This can be a very useful capability to have in military vehicles as it provides an understanding of the geometrical characteristics of the surrounding environment. For example, to be used by a vehicle's crew to measure the width of a narrow alleyway from a distance and determine if it is wide enough to drive the vehicle through it. A screenshot of this measurement application is shown in Figure 5.2 on the following page.

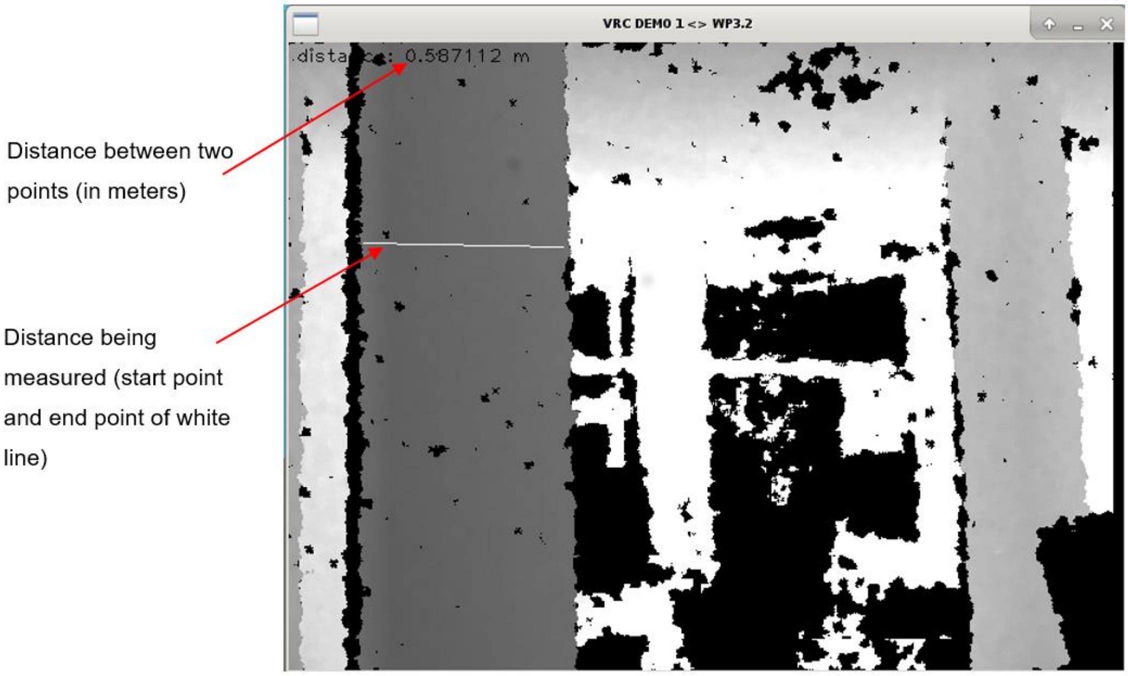


Figure 5.2 Kinect distance measurement

Pattern Recognition

Scenario

The crew of the MCS are holding position within a congested high street and are busy with their routine tasks and are expecting to remain in position for the next 40 minutes.

Behaviour Monitoring

Given the above scenario a group of people that were standing apparently conversing over 40m away from the MCS when it came to a halt, have gradually been moving towards the vehicle over the course of 25 minutes (intentions are not clear).

The fusion system could identify this action due to having the ability to track theoretically an unlimited number of objects in time and space, (this is constrained by resources, computational power, size, weight etc.). The system could provide early warning that over the past 15 minutes this group has been steadily moving closer to the vehicle (using a sporadic trajectory) whilst most other people are generally passing by or moving away after a short period. This does not infer that a threat is imminent, but it can provide an alert to allow for human awareness of this occurrence, which can be then either ignored or actioned upon.

Humans may only notice a threat when it becomes more apparent, say at the 22-minute mark. Humans may also not recognise that a group they observed at the 0-minute mark is the same as a group they observe at the 15-minute mark or be aware of the group or person’s trajectory over the course of those 15 minutes.

This is especially pertinent in a very cluttered environment whilst the crew/commander have their own tasks to attend to or the tracked group is not in crew line of sight.

Facial Recognition

The system could also feasibly alert the crew of known adversaries using facial recognition technologies. Due to the capability of multi target tracking, the system could use the vision technologies in different modes (i.e. as discussed within Chapter 6, 6.5 Capability Management Module (CMM) which supports multi modal fusion capabilities). There could be a mode for navigation or proximity detection and a mode for threat detection using facial recognition, for example, in areas of operations where known threats are known to reside.

Modality switching is suggested as it is likely that computational restraints would not allow for all these tasks/capabilities to be performed simultaneously. However, logically with the required computational resources available it would be possible.

Terrain and Local Surroundings Analysis (change identification)

There is potential to create highly detailed 3D maps (using LiDAR, coupled with temporally matched camera data, as shown in the Kinect example; Figure 5.1 Kinect textured 3D view) of the environment that can be generated throughout operations.

It is feasible to conclude that this data when pre-processed (for instance at base of operations during night-time) can be used the following day in real time to assess changes to the same environment previously observed the day before.

This would allow the system to highlight to the crew (i.e. colourising the object with an overlay on camera feed) possible important changes to terrain (i.e. it appears has been dug and refilled during the last 12 hours, using again a form of pattern recognition).

This capability could be used for possible IED identification or early warning, emergency route planning (Countering infrastructure modifications due to collateral damage).

Reduction of Cognitive Load (a tacit capability)

High-level fusion generates situational meta data that is human identifiable, i.e. the vehicle is too small to traverse through a gap in between buildings or a known threat (person) is approaching the vehicle and is 15 metres away etc.

Therefore, fusion provides the ability to add many sensors whilst reducing the load on the crew of the MCS through the low-level fusion of these various sensing technologies, which is then passed on to the high-level fusion components for inferences to be made and output sent to the HMI/system interface.

Conversely, the fusion process can reduce the number of sensors required by utilising them together rather than as an individual component and therefore provide the ability to infer complex situations with less hardware.

It is a balance that is decided upon and developed during the design of the fusion system.

5.3 UK MoD Collaboratively Developed Use Cases

The following sections present the use cases developed in close conjunction with the UK MoD and NATO representatives. They have been acknowledged and approved by the UK MoD. They were derived from specific capabilities required by the UK MoD to solve specific problems crews of modern Mounted Close Combat (MCC) have faced in operating environments.

5.3.1 Emergency Braking Sub-system – Use Case 1

Below, Table 5.2 describes a use case highlighting the potential exploitation of emergency braking safety sub-systems within military land platforms. The braking force percentages used in this use case are hypothetical.

Table 5.2 Use case: Land platform – Convoy Active Safety

Use case title	Land Platform - Convoy active safety: Use case 1
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Emergency braking system
Scenario	A convoy of four non-tracked vehicles is moving through a congested urban street around 3 metres apart at 30mph. Small arms fire is detected by the crew of the lead vehicle. The convoy begins to accelerate to 40 mph, when the second vehicle receives multiple projectile penetration of the front right tire. The vehicle swerves towards civilian parked vehicles with civilians on the other side of it. Emergency brake assist applies 67% brake force before the driver responds, the third vehicle applies autonomous brake force of 54% as the driver begins to react to the swerving vehicle in front. The final vehicle in the convoy applies 35% braking force before the driver reacts. The braking system prevents any of the vehicles colliding with each other or any of civilian vehicles. The crew react to the ambush; all vehicles retain full capabilities aside from the vehicle with punctured tires.
Roles, Stakeholders, Actors	• Land platform crews, • Civilian infrastructure, • Civilians.

Benefits	• Reduction of cognitive load on crew when operating in cluttered urban environment,
	• Reduction of collateral damage,
	    o Human life,
	    o Civilian local infrastructure,
	• Increased land platform survivability,
	• Increased mission survivability,
	• Enhanced safety for all actors.

Hardware components	• ECU, • Cameras, • Radar, • Lidar, • X-by-wire/actuators.
Software components	• Actuator control, • Object detection, sensor fusion, • HMI/alert control.
CTIL	Due to this sub-system within this use case having dependencies on vehicle systems, power harness and actuators, whilst also being reliant on sensing technologies to perform its function correctly it has been preliminary classified as CTIL 2.

5.3.2 Emergency Braking Sub-system – Use Case 2

Table 5.3 below presents a use case describing the potential exploitation of emergency braking safety sub-systems within military land platforms to enhance safety of civilians in the local vicinity of the MCS. Again, the braking percentages used in this use case are hypothetical.

Table 5.3 Use case: Land Platform - Civilian protection in urban environments

Use case title	Land Platform - Civilian protection in urban environments: Use case 2
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Emergency braking system – predictive civilian protection
Scenario	Crew have been taking part in peacekeeping operations within a congested urban environment. Their vehicle has been surrounded by many civilians/pedestrians and children playing whilst parked with the crew communicating with the local civilians. Some of the children are excited due to the crew and vehicle's presence, as the vehicle moves away another group of children a few metres away they run in front of the platform. The emergency braking system immediately activates at 75% the driver manages to swerve and stop the vehicle before any collision takes place, the accident is avoided.
Roles, Stakeholders, Actors	• Land platform crews, • Civilian infrastructure, • Civilians.

Benefits	• Improved reaction time (compared to humans) in rapidly evolving events,
	• Reduction of cognitive load on crew when operating in cluttered urban environment,
	• Reduction of collateral damage,
	    o Human life,
	    o Civilian local infrastructure.

Hardware components	• ECU, • Cameras, • Radar, • Lidar, • X-by-Wire/Actuators.
Software components	• Actuator control, • Object detection, sensor fusion, • HMI/alert control.
CTIL	Due to the sub-system within this use case having dependencies on vehicle systems, power harness and actuators, whilst also being reliant on sensing technologies to perform its function correctly it has been preliminary classified as CTIL 2.

5.3.3 Parking Assist Sub-system – Use Case 3

The use case described below, Table 5.4 presents an example of exploitation for parking assist safety sub-systems within military land platforms that are being operated within a base by a single crew member.

Table 5.4 Use case: Land Platform - Single crew land platform manoeuvres

Use case title	Land Platform - Single crew land platform manoeuvres: Use case 3
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Parking assist – Camera driven
Exploitation Scenario	The crews of a tracked MCS are preparing for a mission within their base of operations. They are required to be deployed with their vehicle as soon possible as the mission is urgent. Their vehicle needs to be re-armed and vital systems need to be checked by an engineer within the compound. For these tasks to be completed the vehicle first needs to be moved to one section of the compound for re-armament and then to another section of the compound for inspection. An engineer within the base uses the surround camera technology to manoeuvre the vehicle alone whilst having his/her head out of the hatch for forward motion (glancing at the camera feeds below the hatch). For reverse motion, the driver solely uses the surround camera view with low-speed manoeuvres and completes the vehicle mission preparations without the assistance of other crew members/military personnel. During this time, the crew of the MCS who are about to be deployed have been in their mission briefing preparing for the upcoming mission.
Roles, Stakeholders, Actors	• Vehicle operator, • Military personnel, • MCS crews.
Benefits	• Allows single crew member to drive the vehicle without additional help from outside the vehicle, • Safety is increased for all personnel within vehicle vicinity, • Less military personnel are required to manoeuvre vehicles, increasing manpower, crew/military personnel efficiency.
Hardware components	• Vision system (cameras, cabling), • ECU for vision processing, • HMI.
Software components	• Camera stitching algorithms (OEM supplied); • HMI augmented reality overlay processing.
CTIL	The sub-system has been given the classification of CTIL 1 due to being a semi-closed system. Normally these systems come as complete packages end to end and only require power feeds to sensors, ECU and HMI. However, they could offer basic configuration and supplementary data to other systems (directing camera feeds to another display/HMI, for example).

5.3.4 Alternative Parking Assist Sub-system – Use Case 4

The use case presented within Table 5.5 below describes a use case for the ultrasound sensing technologies providing simple surround object detection with audible alarms. This would only be applicable for short-barrelled vehicles (barrel does not extend beyond vehicle chassis).

Table 5.5 Use case: Land Platform - Turning circle collision mitigation

Use case title	Land Platform - Alternative parking assist technologies for turning circle collision mitigation Use case 4
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Alternative parking assist technologies
Exploitation Scenario	A tracked vehicle is stationary in a confined street with vehicles parked on both sides leaving limited space around the MCS. The crew receives orders to turn around and return to a previous position held earlier. The driver activates the manoeuvring sub-system enabling the HMI information screen (providing simple a top-down view of objects around the vehicle) and begins to make the rotational manoeuvre. The operator can clearly see and hear the proximity of the surrounding vehicles and has enough space (in this instance) to perform the manoeuvre safely. The crew complete the rotational manoeuvre and proceed as ordered.
Roles, Stakeholders, Actors	• MCS crews, • Civilians, • Infrastructure local to vehicle, • MCS.
Benefits	• Provides increased situational awareness to the crews of MCS, • If the crew are under armour the system can provide alerts of objects surrounding the vehicle and with additional algorithm development can warn of potential collisions if attempting to rotate vehicle (tracked vehicle turning circles for example).
Hardware components	• Ultrasound range detecting sensors, • Basic ECU, • Basic alert system with staggered beeping that decreases the timing between beeps as an object moves closer to a sensor/'s, • HMI showing range to object in metres.
Software components	• Alert system control, • Sensor reading algorithms, • HMI display manager for displaying objects around vehicle.
CTIL	The technology presented within this use case has been classified as CTIL 1. This is a self-contained system and would require no data input or output from other vehicle sub-systems and would likely not incorporate resource management (offering only a simple on/off state). Would require only a power source (likely taken from the vehicle's power harness).

5.3.5 Alternative Parking Assist Sub-system – Use Case 5

The table below, Table 5.6 presents a simple use case for this system that could be quickly integrated and utilised for around vehicle object detection enhancing crew situational awareness within MCSs.

Table 5.6 Use case: Land Platform – Enhanced situational awareness

Use case title	Land Platform - Alternative parking assist technologies for enhanced situational awareness: Use case 5
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Alternative parking assist technologies
Exploitation Scenario	A military vehicle is parked within a quiet street in a built-up urban area late in the evening with lower light levels and only a few civilians occupying the street. The crew are currently under armour and busy with various tasks when a civilian begins approaching the vehicle from the rear right side. The civilian is holding a metal container in his right hand. As the civilian draws to within 10 metres of the vehicle the audible beeping begins and increases in frequency as the civilian closes to within 7 metres of the vehicle. The crew are alerted to an object approaching and react accordingly.
Roles, Stakeholders, Actors	• MCS crews, • Civilians.
Benefits	• Provides increased situational awareness to the crews of MCS, • If the crew are under armour the system can provide alerts of objects approaching the vehicle and from which direction the vehicle is being approached from.
Hardware components	• Ultrasound range detecting sensors, • Basic ECU, • Basic HMI/alert system with staggered beeping that decreases the timing between beeps as an object moves closer to a sensor/'s. Additional LED display showing range to object in metres.
Software components	• Alert system control, • Sensor reading algorithms.
CTIL	The technology presented within this use case has been classified as CTIL 0. This is a self-contained system and would require no data input or output from other vehicle sub-systems and would likely not incorporate resource management (offering only a simple on/off state). Would require only a power source (likely taken from the vehicle's power harness).

5.3.6 Rear Cross Traffic Alert Sub-system – Use Case 6

Below Table 5.7 describes the use case for Rear Cross Traffic Alert safety sub-system providing barrel strike mitigation coupled with turret rotational assistance/strike warning.

Table 5.7 Use case: Land Platform - Barrel strike early warning and turret rotation assistance

Use case title	Land Platform – Barrel strike early warning and turret rotation assistance: Use case 6
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Rear cross traffic alert system
Exploitation Scenario	A platoon of Main Battle Tanks (MBT) along with Infantry Fighting Vehicles (IFV) and dismounted soldiers are pushing into a city high street leading an assault operation. The heavy armour is providing cover for the IFV and for the dismounted troops by staying close to the sides of the street, the dismounted soldiers cover by the heavy armour from insurgent weapons fire coming from surrounding buildings. Given the elevation of the turret from the ground with the radar sensors being mounted at the base of turret (2 at the front and 2 at the rear) the crew of the heavy armoured vehicle can successfully rotate the turret when required by utilising the HMI displaying the radar tracks data avoiding barrel strikes whilst also avoiding rear turret strike (when the turret of the tank overhangs the main chassis during rotational actuation).
Roles, Stakeholders, Actors	• Land platform crews, • MCS, • Civilian infrastructure.
Benefits	• Likely to reduce or mitigate barrel/turret collisions when slewing the turret, • Provides warnings to the crew whilst they remain under armour, • MCS/mission survivability is increased.
Hardware components	• ECU, • Radar.
Software components	• Basic sensor fusion OEM supplied, • Alert system control, • System deactivation control to provide signature emission control.
CTIL	The technology presented within this use case has been classified as CTIL 2. This use case can use the technology as a self-contained system and would require data output from radar sensors to HMI to inform crew of likely turret collision with displayed radar tracks. Would likely not incorporate resource management (offering only a simple on/off state). Would require only a power source (taken from the vehicle’s power harness for example). This system would likely need to be modified/configured before installation.

5.3.7 Rear Cross Traffic Alert Sub-system – Use Case 7

Use case 7 shown below within Table 5.8 highlights simple object detection utilising the system for its intended purpose. Primarily this could be useful for single crew manoeuvres within the base of operations.

Table 5.8 Use case: Land Platform – Object detection for vehicle manoeuvring

Use case title	Land Platform – Object detection for vehicle manoeuvring: Use case 7
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Rear cross traffic alert system
Exploitation Scenario	The crew of an MCS are manoeuvring a large vehicle out of a hanger type structure, there are blind spots in front of the vehicle and the base of operations is very busy in preparation for a large deployment. The system alerts the driver to movement (another vehicle is about to pass close to the structure entrance) as the vehicle's nose begins to protrude out of the structure's entrance. The banksman guiding the vehicle out of the structure signals the driver to stop, however, the driver has already begun braking as the system provided the audible alert before the driver saw the signal to stop. Reducing the risk of any collision.
Roles, Stakeholders, Actors	• Vehicle operator, • Military personnel, • MCS crews.
Benefits	• Likely to reduce accidental collisions when pulling out of closed areas (restricted field of view), • Safety is increased for all personnel within vehicle vicinity.
Hardware components	• ECU, • Radar.
Software components	• Basic sensor fusion OEM supplied, • Alert system control.
CTIL	The technology presented within this use case has been classified as CTIL 0. This use case can use the technology as a self-contained system and would require no data input or output from other vehicle sub-systems and would likely not incorporate resource management (offering only a simple on/off state). Would require only a power source (taken from the vehicle's power harness for example).

5.3.8 Combined COTS Safety Sub-system – Use Case 8

The scenario below Table 5.9 describes a more complex but feasible exploitation of this technology if coupled with a vision system (COTS parking assist safety sub-system) capable of threat identification (additional algorithms and processing) triggered by the object detection of the rear cross traffic alert safety sub-system.

Table 5.9 Use case: Land Platform – Combined safety sub-systems for around corner view/threat detection

Use case title	Land Platform - Around corner view, threat identification: Use case 8
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Rear cross traffic alert system & Parking assist (camera driven) – additional algorithm development required
Exploitation Scenario	Whilst a tracked vehicle is moving slowly through a deserted urban environment that is known to contain hostiles, the vehicle approaches a crossroads of a built-up street. The front mounted radar detects movement just around the corner as the nose of the vehicle approaches the corner of the structure to its left, the radar object detection triggers the camera threat identification routines. The camera threat detection is activated and assesses the object to be a man with a Rocket Propelled Grenade (RPG). Immediate alerts are provided to the crew who are able to take evasive manoeuvres before the vehicle is clearly visible to the hostile by deploying smoke and reversing.
Roles, Stakeholders, Actors	• Land platform crews, • Red force, • Civilian infrastructure.
Benefits	• Increased situational awareness in urban environments, • Potential for round corner viewing and threat detection, • Increased land platform survivability, • Increased mission survivability.
Hardware components	• ECU, • Radar, • Camera/vision system.

Software components	• Complex sensor fusion of:
	  o Radar object detection triggering camera threat identification,
	  o Camera based threat identification,
	  o Classification of threats.
	• Integration into HMI/BMS.

CTIL	The technology presented within this use case has been preliminarily classified as CTIL 3. Due to the system requiring data from multiple sub-systems to operate correctly. This use case would also require the presented technology to be fully integrated into resource management and system HUMS information. Additional processing and algorithms will need to be incorporated to enable this capability.

5.3.9 Combined COTS Safety Sub-system – Use Case 9

Table 5.10 describes a more complex use case in which MCS local situational awareness is enhanced by allowing the sensor data from all installed COTS safety sub-systems to be available (through a GVA adapter/gateway). This allows further processing of all data into a coherent overview of the current local environment. This use case presents an example of multi target tracking in a cluttered urban environment with pattern recognition and early warning.

Table 5.10 Use case: Land Platform – Combined safety sub-systems for enhanced situational awareness

Use case title	Land Platform – Enhanced situational awareness - Use case 9
Domain	Land Systems COTS automotive safety sub-systems exploitation
Technology	Multiple safety sub-systems & additional processing algorithms required
Exploitation Scenario	The crew of the MCS are holding position within a congested high street and are busy with their routine tasks and are expecting to remain in position for the next 40 minutes. A group of people that were standing apparently conversing over 40m away from the MCS when it came to a halt, have gradually been moving towards the vehicle over the course of 25 minutes (intentions are not clear). The fusion algorithm identifies this action due to having the ability to track many objects in time and space. The system provides an early warning to the crew. Identifying that over the past 15 minutes this group has been steadily moving closer to the vehicle (using a sporadic trajectory) whilst most other people are generally passing by or moving away after a short period. The crew respond accordingly and are now aware of a potential threat.
Roles, Stakeholders, Actors	• Land platform crews, • Civilian infrastructure, • Civilians.
Benefits	• Increased situational awareness in urban environments, • Increased land platform survivability, • Increased mission survivability.
Hardware components	• Multiple ECU, • Radar, • Camera/vision system, • LiDAR.
Software components	• Complex sensor fusion utilising all installed safety sub-systems data, • Integration into HMI/BMS.
CTIL	The technology presented within this use case has been preliminarily classified as CTIL 3. Due to the system requiring data from multiple sub-systems to operate correctly (GVA adapters/gateways). Would require additional data modelling if using DDS as a transport mechanism. Complex algorithm development and HMI development would also be required to enable this capability.

5.3.10 Platooning Technologies: Circa 2035 – Use Case 10

Table 5.11 below, provides a future use case highlighting the benefits of having integrated COTS platooning technologies into military land platforms allowing them to cooperate with civilian Intelligent Transport System V2X infrastructure for traversing route through the UK's public roadways. The CTIL level has been omitted due to the theoretical nature of this use case.

Table 5.11 Use case – Land platform platooning technology ITS cooperation circa 2035

Use case title	Land Platform - Convoy active safety: Use case 10 (circa 2035)
Domain	Land Systems – Intelligent Transport System Cooperation
Technology	Platooning – Connected convoy
Scenario	The UK's Intelligent Transport System is now fully realised and on many of the major roadways it is illegal to manually operate vehicles that are not equipped with the current V2X communication protocols, and which cannot interact with transport system infrastructure. Five Infantry Fighting Vehicles are being relocated for routine maintenance and have a 40 mile journey to complete. A single military engineer operates the lead vehicle with the four following vehicles in platooning mode. Specific configuration of DSRC protocols does not allow civilian vehicles to join the military platoon during the journey (as civilian vehicles normally behave within this scenario). However, as all the military land platforms within the platoon are equipped with the necessary communication protocols and standards (DSRC/WAVE, for example) and are platooning capable, they traverse the route whilst safely interacting with the level 5 autonomous civilian vehicles populating the UK motorways. Thus, allowing a single crew member to safely complete the transfer of five IFV from one location to another.
Roles, Stakeholders, Actors	• Civilian ITS infrastructure, • Military connected convoy, • IFV driver/operator;
Hardware components	• ECU, • Multiple sensor technologies, • LSRG components, • DSRC standards, • X-by-Wire/actuators.
Software components	• Actuator control, • Object detection, sensor fusion, • DSRC protocols (WAVE), • HMI/alert control.

5.3.11 Platooning Technologies: Circa 2035 – Use Case 11

Table 5.12, provides a future use case highlighting the benefits of having integrated COTS platooning technologies into military land platforms allowing them to cooperate with civilian Intelligent Transport System V2X infrastructure for traversing through future urban environments gathering tactical information as they interact with the civilian V2X infrastructure. The CTIL level has been omitted due to the theoretical nature of this use case.

Table 5.12 Land platform platooning technology ITS cooperation within the urban environment circa 2035

Use case title	Land Platform - Convoy active safety: Use case 11 (circa 2035)
Domain	Land Systems – Intelligent Transport System Cooperation
Technology	Platooning – Connected convoy
Scenario	A convoy has been tasked with evacuating civilians from a local building 4km from their current position. Both locations are heavily populated civilian areas with level 5 autonomous vehicles traversing the roadways as part of an Intelligent Transport System. Adversaries are known to be in the area and caution is required. There is currently heavy congestion on many roads and the commander begins to plan a route using information gathered from the ITS infrastructure with the aid of the platform's IDA. Two routes are apparently available that offer a reduced time to destination. One route has reduced congestion over the main route initially planned; however, the second route (through side streets and a short, larger road with no side turnings) appears almost completely clear of local civilian vehicles. Considering the information available the commander decides to take the first route as using the information gathered from the ITS infrastructure the local civilians driving patterns appear to be completely avoiding the second route. This could be an indication of a possible planned ambush. The convoy proceeds to safely traverse the second route cooperating with the ITS and civilian vehicles and reaches the evacuation point successfully.
Roles, Stakeholders, Actors	• ITS, • Civilian level 5 autonomous vehicles, • Red force, • Allied convoy.
Hardware components	• Multiple ECU, • Multiple sensor technologies, • LSRG components, • X-by-Wire/actuators, • DSRC technologies, • IDA technologies.
Software components	• Actuator control, • Object detection, sensor fusion, • HMI/alert control.

5.4 Commercial Technology Integration Levels (CTIL)

Presented within this section will be the Commercial Technology Integration Levels themselves shown in Table 5.13, page 130. Four different levels of commercial technology integration have been identified, and are based on the analysis of the information exchange supported by the system (e.g. sensor data, status and configuration) and the level of resource (power) management permitted by the system.

Based on the research published from this body of work [99, 100] and meetings with the Defence Science and Technology Laboratory (DSTL) representatives through various open days and project related meetings it is indeed a benefit to include a classification metric that could be used to inform a selection framework.

To evaluate (score) a given technology with the objective of assigning a given CTIL level to the technology, extensions to the VSI Standards and Guideline metrics, published here [101], are suggested. This assessment framework attempts and succeeds in many ways to provide a semi-objective (semi-quantitative) assessment as to whether or not any given sub-system / architecture design is VSI compliant. Published in late 2007, whilst old, does provide a useful example of relating the complex assessment of multiple technologies with varying components. The objective is to provide a numerical output that can then be average or additive in nature to allow a given sub-system or sensing technology to be assigned a specific CTIL level. The examples provided within 5.6 and 5.7 are simply high-level examples of how a CTIL classification could be derived, this process is out of the scope of this body of work and would constitute further research.

To aid designers, engineers and system integrators in determining the level of integration and consequently the exploitation possibilities of the candid technologies, Commercial Technology Integration Levels (CTILs) are proposed and described in Table 5.13. On the one hand, CTIL 0 represents systems that are simple to add to a vehicle platform but support or offer no exploitation beyond their intended application. On the other hand, CTIL 3 represents systems that are more complex and challenging to integrate but provide greater opportunities for exploitation as described throughout Chapter 4, page 74.

Table 5.13 Commercial Technology Integration Levels (CTILs)

Commercial Technology Integration Level (CTIL)	Description
CTIL 0	• Self-contained ('bolt-on') solution with own sensor(s), processing unit(s) and outputs/display(s), • No data input or output from the system, • May use own power source or use vehicle provided power. Unlikely to have any provisions for resource management, • Example: a self-contained parking assist (sensors) system.
CTIL 1	• Functionally self-contained solution with own sensors, processing and outputs / displays, • No data input into or output from the system is required to provide the baseline capability. However, the system may accept supplementary data, which when available will be used to improve the performance of the system, and/or provide supplementary data that can be exploited by other systems, • May use own power source or use vehicle provided power. Unlikely to have any provisions for resource management beyond enabling/disabling the system, • Example: Rear cross traffic alert.
CTIL 2	• Upgrade solution with own sensors and processing (software and/or hardware) that depends on other systems to deliver the complete capability, • May require input from other systems/sensors in order to operate, or provide an output that is needed by other systems to provide the complete capability, • May use vehicle provided power and support simple integration with vehicle's resource management (providing status information and accepting simple configuration commands), • Example: Emergency braking system.
CTIL 3	• These technologies use common interfaces e.g. CAN, Ethernet etc. with a provided data sheet detailing communication protocols and requirements, message / command structure, • Fully integrated (software only, or software/hardware) solution, which may use vehicle hosted services (sensors, processing, communications, and displays), • Requires input from other systems/sensors in order to operate. The system also provides other systems with the output needed to achieve the complete capability. The system is effectively an integral element of the end-to-end capability, • Fully integrates with vehicle resource management enabling capability reconfiguration and providing system's status and health information,

5.5 Evaluation Matrix

A draft matrix for the evaluation of commercial and automotive sensing technologies is designed based on the VSI Metrics [101]. The CTIL Metrics, aim to provide a useful guide for the assessment of the technology application in the domain of military land vehicles. The CTIL Metrics could have the main dimensions of: Operational, Performance, Integration Specifications and Costs, with variable sub-dimensions for each of the main dimensions. It must be noted that the following is a suggested example to provide the reader with an overview of the discussion held with the UK MoD and previous research.

The evaluation matrix is specific for the comparison and assessment of different sensing technologies that are developed for the automotive and consumer markets and their applicability to the military land vehicles. The objective behind this matrix is to aide vehicle designers, engineers and integrators in identifying candid technology and assessing potential capability for exploitation in military vehicles. This can be of significant help in meeting Urgent Operational Requirements (UOR), planning upgrades and designing future vehicles.

The evaluation matrix (Table 5.16, page 133) allows you to potentially score individual parameters and sub parameters taken from the metrics shown below in Table 5.14.

Table 5.14 CTIL evaluation dimension parameters

	Parameters	**Sub-parameters**
CTIL Evaluation Dimensions Sensing Technologies	Operational Specification	Range
		Field of View (FoV) (horizontal, vertical)
		Resolution
		Accuracy
	Performance Specification	Degraded Visual Environments (DVE) (fog, rain, smoke)
		Electromagnetic Interference (EMI) tolerance, Electromagnetic Compatibility (EMC)
		Temperature
		Vibration
	Integration Specification	Data (type, size, rate)
		Interface(s) (type, QoS)
		Power ratings
	Costs	Direct cost (purchasing price)
		Indirect costs

The level of detail included in the evaluation matrix can vary depending on the desired level of evaluation. For example, the matrix can be used to compare and assess different technologies (e.g. comparing LiDAR with radar), and it can also be used to compare and assess different products of the same technology. Table 5.15 on the following page provides a breakdown of the CTIL evaluation dimension parameters described above in Table 5.14.

Table 5.15 CTIL evaluation dimension parameters breakdown

Parameter type description	Sub parameter type example

Operational parameters
 	
Provides an understanding of the capability that can be obtained from a specific technology.
	• Range:
	  ○ This parameter considers the effective range of any given sensing technology. All sensing technologies have an effective range constraint for obtaining reliable readings,
	• FOV:
	  ○ This parameter describes any given sensors field of view, normally presented in a range of degrees,
	• Resolution:
	  ○ This describes effectively the smallest measurement a sensing technology can indicate. It is not a reference or metric related to accuracy,
	• Error rate / accuracy:
	  ○ This describes the error rate as presented by the manufacturer, normally this is presented in a percentage metric (i.e. +/- 5%). This accounts for not only manufacturing tolerances but also sensing performance (e.g. ultra sound sensors might have a slightly increased error due to thicker / thinner air, although this would be minor error rates).

Performance parameters
 	
Essentially provide a measure of performance (MOP) or a measure of effectiveness (MOE) (or both) by providing an understanding of the level of operation supported by the technology/product in environments typically found in military operations.
	• DVE behaviour,
	  ○ This sub-parameter describes the given sensing technologies behaviour in degraded visual environments (i.e. brown out). This metric is derived from the impact on the four Operational Specification sub-parameters,
	• EMI behaviour:
	  ○ This describes the technology's profile within the electromagnetic spectrum, including conformity to regulations and EM output,
	• Temperature specifications:
	  ○ This directly observes the operating temperature range as described within the manufacture / supplier data sheet for any given component,
	• Vibration specifications:
	  ○ This directly observes the vibration resistance range / tolerance as described within the manufacture / supplier data sheet for any given component.

Integration parameters
 	
Provide an indication of the resources requirements/cost on the vehicle electronics infrastructure in order to support the addition of the technology.
	• Data:
	  ○ This is an important parameter when assessing integration properties of a given technology. It describes the data structure of a given technologies payload coupled with data rate per second,
	• Physical interface:
	  ○ Described within this parameter are the physical network connections (i.e. are they proprietary or industry standard).
	• Software interfaces / protocol:
	  ○ This describes the available software interfaces to the network (i.e. are they proprietary or industry standard, OSI stack), including Quality of Service (QoS),
	• Power specifications:
	  ○ Describes the technology's power requirements, again does it conform to known standards or are the requirements more bespoke.

Costs parameters
 	
Can be used to identify the short and long-term investment needed to acquire and maintain the technology.
	• Direct purchase costs,
	• Time to integrate:
	  ○ based on engineer skill level,
	  ○ output from previous dimensions.

5.6 Example of an evaluation matrix (LiDAR, RADAR)

Table 5.16 Evaluation matrix example

[Technology] – Product	Operational				Performance				Integration			Costs	
	Range	FoV	Resolution	Accuracy	DVE	EMI/EMC	Temperature	Vibration	Data	Interface(s)	Power ratings	Direct cost	Indirect costs
[LiDAR] – Velodyne Puck VLP-16	100m	± 15º vertical, 360º horizontal	300k/600k points per second, 2.0° vertical angular resolution, 0.1° – 0.4° horizontal angular resolution	±3cm			Operating temp: -10ºC to +60ºC. Storage temp: -40ºC to +105ºC	Shock: 500m/s^2 amplitude, 11ms duration. Vibration: 5-2 kHz, 3G$_{rms}$	100 Mbps Ethernet, UDP packets: time of flight distance measurement, calibrated reflectivity measurement, rotation angles, synchronised time stamps (µs resolution)	Ethernet	Class 1 laser, 903nm wavelength, 8W power consumption, 9-18V operating voltage	$8k per unit	TBD
[LiDAR] – Ocular RobotEye RE05	30m	± 70º vertical, 360º horizontal	30 kHz, azimuth & elevation axes res.: 0.01º	±50mm			-20ºC to +50ºC	N/A	N/A	Ethernet	50W @ 24V	$19k per unit	TBD
[LiDAR] – SLAMTEC RPLIDAR A2	0.15 - 6m	2D, 360º horizontal	4000 samples/s, 10-15 Hz,	Distance res.: 1%, angular res.: 0.9º			0ºC to +45ºC	N/A	Approx. 160kb/s	TTL UART	1.5A @ 5V	£400 per unit	TBD
[Radar] – Continental ARS408 Premium	250m (far range), 70m (short range), 20m (near range)	Azimuth angle:18º far range, 80º short range, 120º near range. Elevation angle = 14º for range, 20º near range	1.79m at far range, 0.20m at near range	±0.40m at far range, ±0.05m at near range			Operating temp: -40ºC to +85ºC. Storage temp: -40ºC to +90ºC	Shock: 500m/s^2 @ 6ms. Vibration: 20 [(m/s^2)^2/ Hz] @ 10 Hz, 0.14 [(m/s^2)^2/ Hz] @ 1 KHz peak	500 kbit/s, up to 8 CAN ID	CAN	At 12VDC, 6.6W typical and 12W peak	€2690 for 1 unit, €940 per unit for order of 10 units.	TBD

It should be noted that the research on CTILs and the evaluation matrix is preliminary and discusses the generic characteristics of commercial technologies exploitation in military vehicles. The proposed framework can be refined and adapted to individual cases as appropriate.

5.7 Conclusion

This chapter provided eleven detailed use cases approved by and developed in conjunction with the UK MoD (crew and DE&S, DSTL representatives), which were used in the development of the CTIL COTS integration levels.

Due to the long-term requirements of military procurement the CTIL classification framework can support initial procurement decisions from a wide range of audiences that may be involved, consulted, during the complex, early procurement stages. CTIL has been shown to enable an early indication of not only financial and technical costs when selecting a candid COTS technology for use within military vehicles but also the capability gained versus costs.

- CTIL levels highlight the constraints of using simple but complete self-contained safety sub-systems (such as parking assist). Whilst there are potential benefits to using such technologies in a non-combat environment (e.g. base of operations), such technologies promote vendor lock in. If any technologies in CTIL level 1 were to be selected it would be beneficial to only select low-cost solutions that are considered ‘throw away’.
- Conversely, the CTIL levels highlight the benefits of investing in either the sensing technologies themselves or highly configurable safety sub-systems (ADAS). Whilst individual sensing technologies would be initially expensive to integrate at this time due to requiring GVA infrastructure to support them they offer the highest long-term benefits.

One notable constraint of the CTIL levels is a lack of human factors considerations and safety / security.

The following chapter presents the Generic Sensor Fusion Electronic Architecture (GSFEA) to facilitate the integration of modern COTS sensing technologies within the GVA environment.

6 Generic Sensor Fusion Electronic Architecture

6.1 Introduction

To fully exploit Commercial-Off-The-Shelf (COTS) sensing technologies described within the previous chapters, a novel, modular, multi-mode, generic sensor fusion architecture is proposed based on the advent of new commercial automotive mobility technologies being developed by the automotive industry [42]. These new advances in sensing technologies and their cost reductions have promoted a large, renewed research drive into the implementation of sensor fusion architectures. The purpose of which is to provide vehicles with a reduced error rate (increased validation) regarding the sensor information being provided; which in turn when used with data fusion provides the vehicle with an exceptionally detailed and complex view of the local environment [7].

In general, as discussed within Chapter 3, Sensor Fusion Architectures and Networks, it could be said that sensor fusion is as it sounds; the fusion of multiple sensor data being combined to increase the verification of a detectable event occurring. In other words, the sum of the system exceeds its individual parts [47, 50] and is not simply an additive process.

The application of a sensor fusion architecture within military land systems to exploit sensing technologies would provide the following benefits:

- The ability to track objects with temporal and spatial attributes associated with them, beyond human capabilities,
- As the number of sensors being developed and used within vehicles increases, especially within military vehicles, the same useful information could be produced with less sensors but with stronger intelligence behind them (the fusion process),
- For systems that are mission critical, these systems could make use of or require, accurate, validated information of an event, such as Defensive Aids Systems (DAS),
- Reduction of cognitive load during possibly high stress/load scenarios by fusing multiple sensor data. Thereby, rather than providing the crew of the vehicle many sensor readings which they have to make their own inferences on, the system fuses all the sensor readings returning a single piece of information or inference of the data.

Essentially, the fusion process adds intelligence to the sensing technologies far beyond their capabilities or human capabilities, examples are as discussed in previous chapters:

- Advanced pattern recognition (faces, times, places etc.),
- Terrain and local surroundings analysis,
- Terrain modification since previous observational data (i.e. possible IED identification/early warning),
- Route planning (i.e. countering infrastructure modifications due to collateral damage),
- Collate many sensor data concurrently (reducing cognitive load, tacit capability).

The following excerpt (from a special session held at Cambridge University) describes so succinctly what has been many of the goals of this architectural research, published after the core research had been completed in 2018, that it is included here as the second and final direct quote contained within this body of work.

"SS12 - Multi-layered fusion processes: exploiting multiple models and levels of abstraction for understanding and sense-making

The exploitation of all relevant information originating from a growing mass of heterogeneous sources, both device-based (sensors, video, etc.) and human-generated (text, voice, etc.), is a key factor for the production of timely, comprehensive and most accurate description of a situation or phenomenon in order to make informed decisions. Even if exploiting multiple sources, most fusion systems are developed for combing just one type of data (e.g. positional data) in order to achieve a certain goal (e.g. accurate target tracking) without considering other relevant information (e.g. current situation status) from other abstraction levels.

The result of single-layer processing is often stove-piped systems dedicated to a single fusion task with limited robustness. This is caused by the lack of an integrative approach for processing sensor data (low-level fusion) and semantically rich information (high-level fusion) in a holistic manner, thus effectively implementing a multi-layered processing architecture and fusion process.

Processes at different levels generally work on data and information of different nature. For example, low level processes could deal with device-generated data (e.g. images, tracks, etc.) while high level processes might exploit human-generated knowledge (e.g. text, ontologies, etc.).

The overall objective is to enhance the sense-making of the information collected from heterogeneous sources and multiple processes for improved situational awareness and intelligence."[102].

The functionality DDS provides (data centricity) has allowed (within the architecture proposed) the real time creation and destruction of publishers and subscribers which dramatically supports a design of a system that can reconfigure at run time or when being applied to varying types of manned / unmanned military land platforms.

The following sections present the engineering approach to the design of the novel architecture along with the 3 major components of the sensor fusion architecture, being the Generic Sensor Interface Architecture (GSIA) and the Generic Sensor Fusion Electronic Architecture (GSFEA) itself, with the novel approach to support a multi modal sensor fusion architecture, along with the Remote Land System Gateway (RLSG) architecture.

6.2 Systems Engineering Approach

The design approach adopted follows the SIMILAR Process (State, Investigate, Model, Integrate, Launch, Assess and Re-evaluate) [103], see Figure 6.1 below.

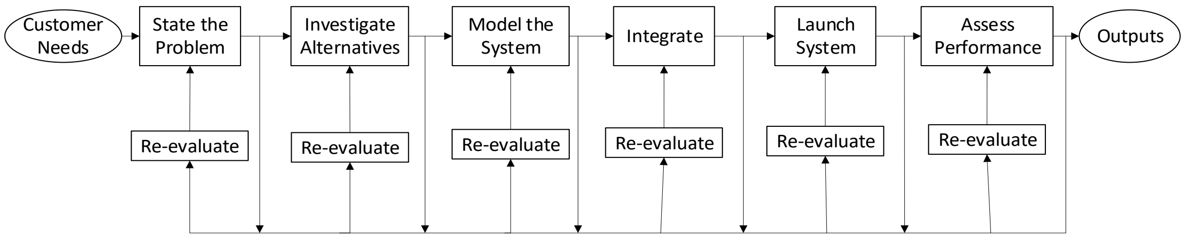


Figure 6.1 The systems engineering process [103]

The above engineering methodology has been selected to allow for rapid design, evaluation and testing of the high-level architecture design, allowing for significant flexibility when designing and implementing this type of rapid and potentially prone to change type of cutting-edge research.

The tools selected for use are as follows:

- IBM Rational Rhapsody,
- Eclipse IDE for C, C++ (multiple versions),
- QT IDE (free licence),
- Microsoft Visio,
- Linux Debian (multiple releases) for development.

6.2.1 Requirements Analysis

Fundamental to the requirements analysis and therefore the overall architecture design is the consideration of safety and security. Careful consideration is paid to each individual module safety and security requirements based on a selection of exploitation scenarios. This analysis is completed once the architecture is implemented as a running demonstrator and Measures of Performance (MOP) are retrievable so as to allow a contrast between MOPs coupled with safety and security implementations, allowing the design to maintain an acceptable level of all three.

To drive the initial design, the definitions for the high-level requirements are created. These are developed using a mixture of stakeholder (UK MOD) inputs along with a prior knowledge and experience, coupled with applied research.

GSFEA User Requirements

Table 6.1 below presents the initial user requirements derived from discussions with the UK MOD.

Table 6.1 GSFEA user requirements

REQ ID	Initial Requirements Table (GSFEA)
	User requirements
IRUR001	The architecture shall provide support for a wide range of COTS sensing technologies.
IRUR002	The architecture shall provide the crew of mounted close combat systems with an advanced situational awareness of their local environment whilst under armour.
IRUR003	The architecture shall provide the dismounted troops of MCS with situational awareness of their local environment.
IRUR004	The architecture shall provide through life cost benefits by adhering to the guidelines laid out by IOA/GVA DefStan 23-009.
IRUR006	The Architecture shall support rapid reconfiguration of capability.
IRUR007	The Architecture shall provide integration of Commercial Off The Shelf (COTS) sensing technologies into military vetronics architectures.
IRUR008	The architecture shall support user control of the sensor/sensors signal emissions.

GSFEA Architectural Requirements

The following table (Table 6.2) presents the expansion of the user requirements shown above to develop the initial architectural requirements for the GSFEA.

Table 6.2 GSFEA architectural requirements

REQ ID	Initial Requirements Table (GSFEA)
	Architecture requirements
IRAR007	The architecture shall comply with the DefStan 23-009.
IRAR001	The architecture must offer support for common communication interfaces currently available (such as CAN / MiLCAN, Ethernet, I2C, SPI, USB).
IRAR002	The architecture must offer support for power requirements of common sensing technologies (12v, 5v, 3.3v, 24v,19v).
IRAR003	The architecture should also provide a common data centric communication interface such as Data Distribution Service (DDS) utilising the OMG Interface Definition Language (IDL).
IRAR005	The architecture shall support a generic modular design approach following IOA approaches.
IRAR004	The architecture shall provide interoperability between various sensing technologies and system data input bus.

GSFEA System Requirements

Below Table 6.3 presents the initial system requirements table derived from the architectural requirements presented above.

Table 6.3 GSFEA system requirements

REQ ID	Initial Requirements Table (GSFEA)
	System requirements
IRSR001	The system must support the ability to allow for future upgrades, modifications and reconfigurations with minimal cost/time impact.
IRSR002	The system must be able to minimise node power consumption.
IRSR003	The system must be able to provide the level of security required by the current application.
IRSR004	The system must be able to provide the level of safety required by the current application.
IRSR006	The GSFEA should provide a DDS Secure V1.0 profile.
IRSR005	The system should be as close to real time (end to end) as possible.

6.3 Architecture Functional Design

The configuration of a sensor fusion architecture's physical topology affects many factors within the system, such as performance, real time concurrency, latencies and therefore, overall system behaviour. These attributes in turn are related to designing a safety-critical environment where the system's behaviour must exhibit a level of determinism. A brief overview of the most commonly accepted topologies has been provided in Chapter 3, 0

Review Sensor Fusion Design Topologies along with their identified benefits and constraints.

An architecture design is proposed that can support real time reconfigurability within system and software implementation and is initially described within Figure 6.2 GSFEA logical model on page 141. A generic approach has been taken with the sensor interface design to allow various / any current or potentially future sensor type to be integrated with the system without the need to redesign any part of the interface. Given that the use cases developed in conjunction with the UK MoD (presented within Chapter 5) are based around the premise (stated by the MoD) that any information is better than no information (it is conceived that even if the system couldn't identify a target above say 50% accuracy, at least the crew would know something is there in a given direction). This capability is supported by the flexibility provided by the Generic Sensor Interface Architecture (GSIA) and the Capability Management Module (CMM).

A fundamental finding of this research is that the described use cases for Mounted Combat Systems are very different to that of autonomous navigation. Therefore, the approach to a sensor fusion architecture design where the system is tightly coupled once designed and built can be challenged. This supports a more flexible architectural approach allowing for real time reconfigurability.

Once the architecture has been developed further (i.e. a running demonstrator) then the interaction between safety and security should be considered and revisions made to the overall system if required, the purpose of which will be to resolve safety and security conflicts whilst maintaining a sufficient level of both. Primary concerns (which will evolve to concrete requirements) are security of data / system, fault tolerance (graceful degradation), determinism and the systems interaction with the military vetronics gateway module whilst maintaining an acceptable level of performance. This has been presented to and accepted by the UK MoD as further research studies for future UK MoD Vehicle Systems Integration (VSI) projects.

The logical model of the proposed Generic Sensor Fusion Electronic Architecture (GSFEA) highlighting the core modules is shown in Figure 6.2.

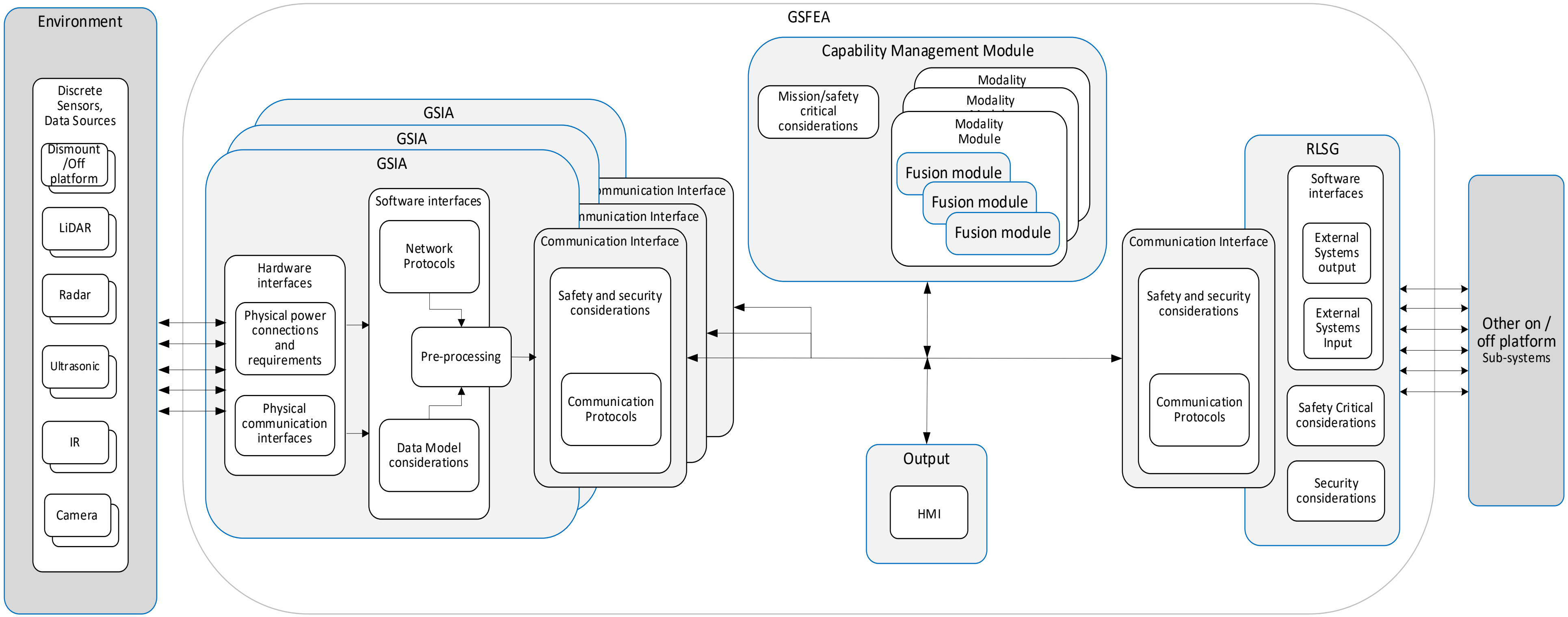


Figure 6.2 GSFEA logical model

The following provides a breakdown of Figure 6.2 GSFEA logical model. Many of the capabilities described are enabled by the use of DDS and the structure of the data model developed during this research, provided within 10.2 Appendix B: GSFEA Data Model .IDL, page 238.

6.3.1 Environment/Discrete Sensors, Data Sources

This module represents the sensor input into the fusion architecture. Sensing technologies refers to the input from physical sensors (e.g. radar, LiDAR, Kinect and sonar etc.). This module also includes current and future dismounted soldiers' equipment as data inputs as this type of data source is becoming more prolific as shown within the current Def Stan 23-012 [31].

6.3.2 Generic Sensor Interface Architecture (GSIA)

The Generic Sensor Interface Architecture (GSIA) allows the GSFEA to have a coherent method for the integration of physical sensors. This module supports sensor data collection from the native sensor interface and outputs the data utilising DDS using a generic data model as the software interface. There is currently no Def Stan 23-009 GVA data model supporting COTS sensing technologies.

This module is covered in further detail within section 6.4 Generic Sensor Interface Architecture, page 143.

6.3.3 Capability Management Module (CMM)

This module could be seen as the core for the fusion system, designed in such a way to accept multiple data sources of multi types (e.g. raw sensor data or edge fused objects lists). The term capability when used within the description of this module refers to the tactical or military operational requirement of any given mission. This module is responsible for managing the current fusion task / tasks based on the fusion module currently loaded.

This is covered in further detail within section 6.5 Capability Management Module, page 158.

6.3.4 Remote Land Systems Gateway (RLSG)

This final module is designed to support the future of The Internet of Battlefield Things (IoBT) [104, 105]. The architecture design consists of various components to manage secure data transfer between the GSFEA and any remote systems. The architecture is detailed further within section 6.6 Land Systems Remote Gateway, page 166.

The following sections provide the reader with the detail of the 3 major modules described above (GSIA, CMM and RLSG).

6.4 Generic Sensor Interface Architecture

6.4.1 Introduction

The Generic Sensor Interface Architecture (GSIA) allows the GSFEA to have a coherent method for the integration of physical sensors. This module supports sensor data collection from the native sensor interface and outputs the data utilising DDS using a generic data model as the software interface. There is currently no Def Stan 23-009 GVA data model supporting COTS sensing technologies.

The aim of the GSIA is to support plug and play (currently however this is extremely ambitious, due to the nature of Mil spec components, it expected that at best plug, configure and play would be achievable) of a variety of sensing technologies and to provide support for multi-capability user configuration. It also enables two-way communication with the sensors so that configuration requests (e.g. sensor start/stop) can be passed to the sensors.

The GSIA can operate within two modes either sending raw sensing data on to further processed, gated and then fused or to allow these processes to be carried out at the sensing object itself (edge fusion) and passing on a simple object list to be processed with other objects lists or raw sensing data. Obviously, the downside of sending object lists is the accuracy or validity or an event or object is reduced, the benefits provide much reduced processing further on in the system and much lower bandwidth used on the network. The models to provide these modes are presented on the following pages within Figure 6.5 Sensor specific data model and Figure 6.6 Sensor independent data model and tracked object lists.

The benefits of a plug and play solution could be significant as it would allow for Urgent Operational Requirements (UOR) to be fulfilled immediately and/or within the area of operations. However, technical constraints currently present significant challenges in providing this capability. Having a system recognise a sensor and integrate that sensor with the rest of the system securely and effectively is very challenging due to the varying and large numbers of commercial sensing technologies available.

6.4.2 DefStan 23-009 GVA Infrastructure Requirements

To facilitate the integration of any communication protocol with the DefStan 23-009 GVA requires an interface to the GVA infrastructure. Key requirements for GVA compliance are noted below taken from the standard (section 5 and section 6 [18]). Figure 6.3 below describes the required GVA interface panel when integrating various sub-systems within the GVA environment. The GSIA adopts these requirements as a starting point and adheres to them to provide a GVA compatible architecture design.

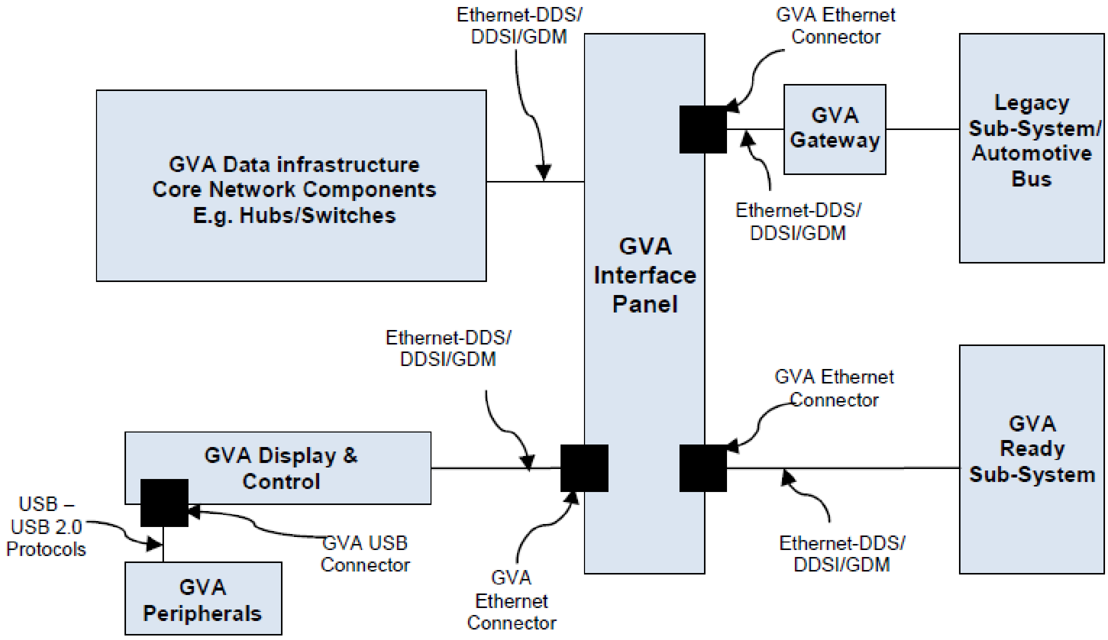


Figure 6.3 Simplified GVA data infrastructure [18]

Table 6.4 presents further, relevant, requirements for data transmission across the GVA infrastructure are as follows (taken from sub-section 6.12.4, section 6.12 Data Infrastructure Messaging Requirements [18]):

Table 6.4 Def Stan 23-009 Part 2 - section 6.12 Data Infrastructure Messaging Requirements [18]

ID	Priority	Requirement Text
GVA_INF_52	N/A	**Messaging**
GVA_INF_90	Key	All [sub-systems] shall use the [GVA Data Infrastructure] and messaging protocols for data distribution
GVA_INF_53	Key	The interface messaging protocol standards used on a [GVA Data Infrastructure] shall be the OMG Data Distribution Service (DDS) v1.2 and DDS Interoperability Wire Protocol Specification v2.1
GVA_INF_54	Key	DDSI configuration shall be as defined by Section 9.6.1 of OMG Document Number formal/2009-01-05 'The Real-time Publish-Subscribe Wire Protocol DDSI Wire Protocol Specification'
GVA_INF_55	Key	The distribution of data on the [GVA Data Infrastructure] shall conform to the GVA Data Model

As per *GVA_INF_55* conformity with the UK GVA Data Model is required, however, the current UK GVA Data Model has no support for automotive COTS sensing technologies or generic sensor fusion therefore an initial sensing technologies data model has been created to support various COTS sensing technologies. Where the sensing technologies could not be procured, simulated sensor data has been used (based on the technologies data sheet, e.g. Velodyne VLP-16 [106]).

6.4.3 Initial proposals - Generic Sensor Interface Architecture

The approach taken defines a generic interface adapter to provide an effective bridge between COTS technologies and Def Stan 23-009 GVA. Additionally, it is designed to support multiple current and future sensing technologies by separating the sensor and the Def Stan 23-009 GVA into two modules. Thus, providing a generic interface to the Def Stan 23-009 architecture through the sensor independent module. These modules are discussed in further detail in the following sections. Figure 6.4 Generic sensor interface concept UML class diagram, describes the initial idea / approach taken to the design of the GSIA. We can see the classes bus object and sensor objects containing attributes passed into the class that can then be used to create a concrete instance of the bus or sensor type required (shown within the specific interfaces). This initial idea formed the basis of the data model design for a generic approach to bus and sensor interfacing within the GSIA and overall, for the GSFEA.

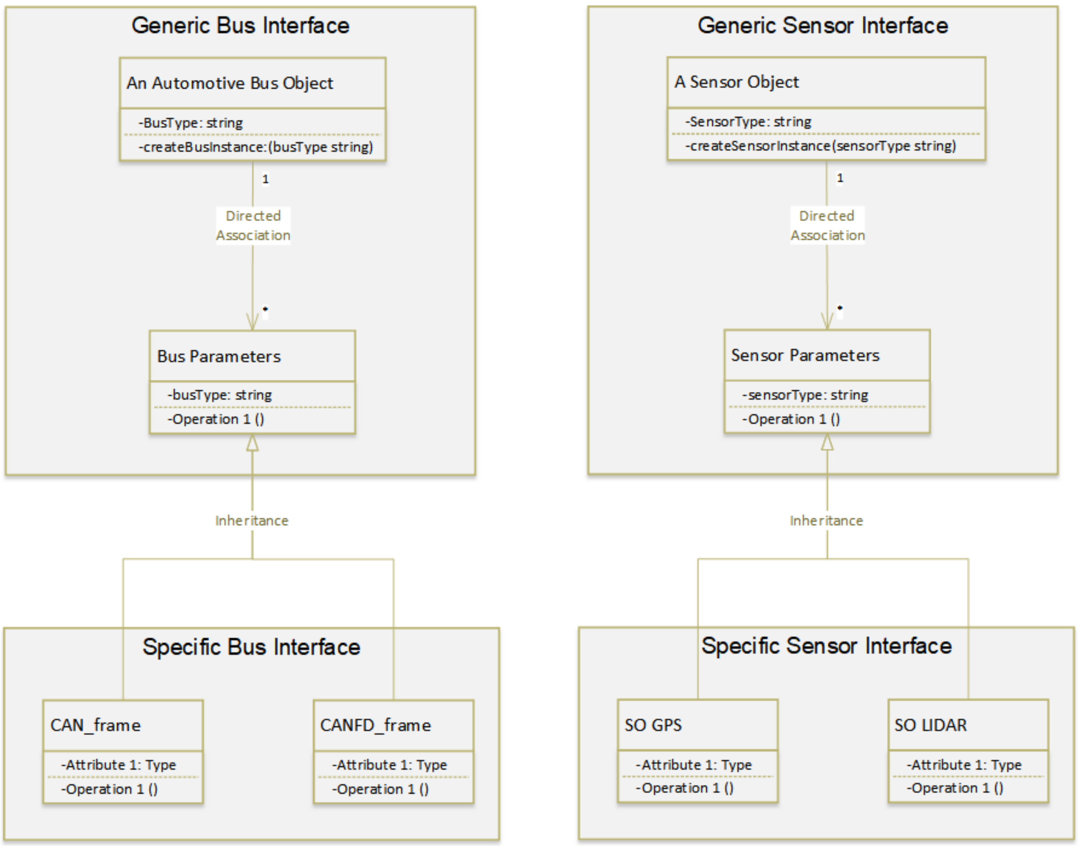


Figure 6.4 Generic sensor interface concept UML class diagram

This design approach also supports a “plug, configure and play” realisation for the GVA and NGVA supporting rapid integration of new technologies into military land platforms that are GVA / NGVA compliant. Over the following sections, the GSIA is presented in further detail, beginning with the GSIA’s sensor data, model-based diagram shown in Figure 6.5.

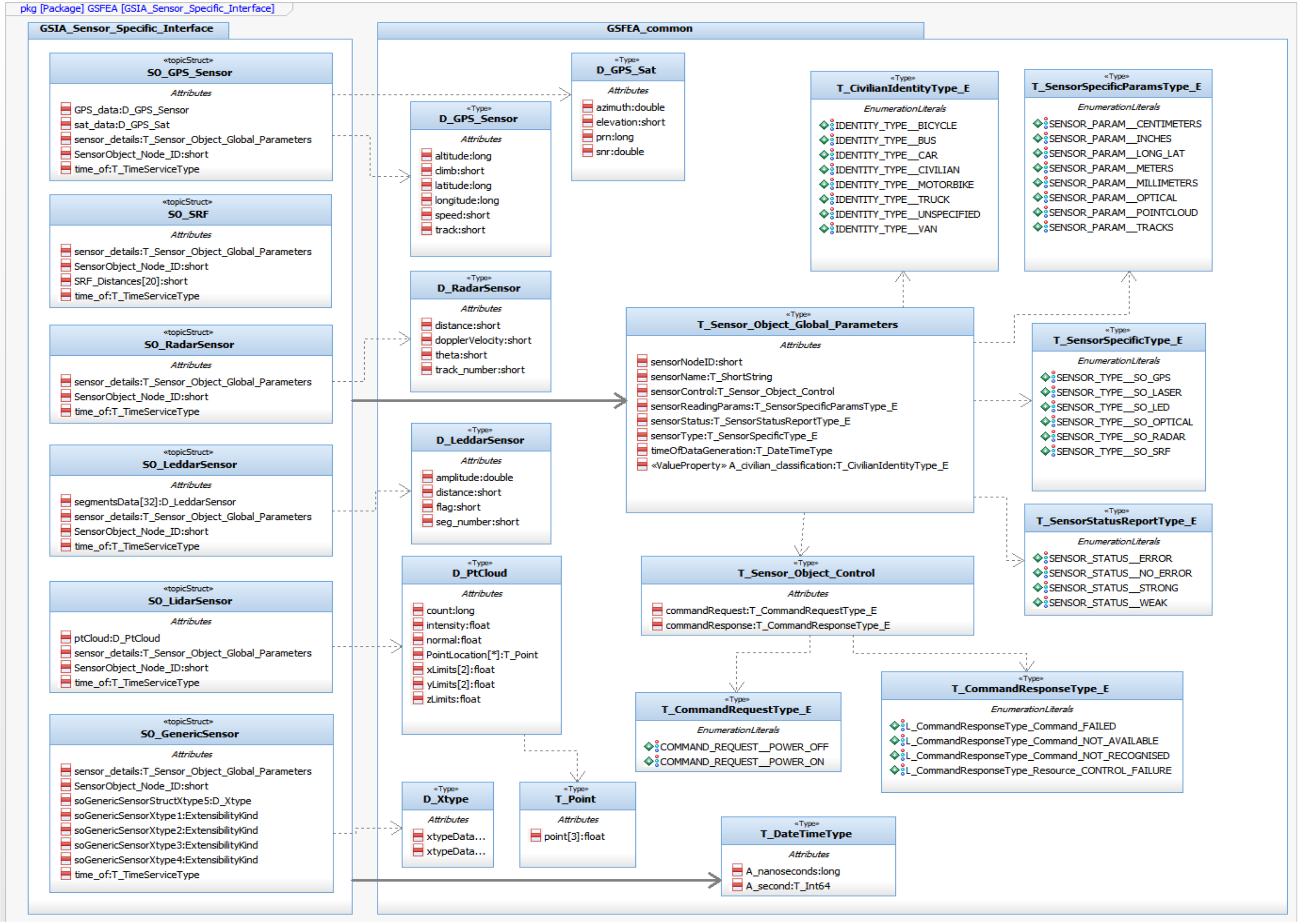


Figure 6.5 Sensor specific data model

Figure 6.5 Sensor specific data model, describes the first component of the GSIA. The model itself follows the GVA / NGVA modelling ethos and can be used with any type of middleware, not necessarily DDS. The GSFEA_common module shown contains all the common data types used by the entire GSFEA. This module consists of the following data types described in Table 6.5.

Table 6.5 GSFEA_common module structure and description

<table>
<tr><th colspan="2">GSFEA_common module</th></tr>
<tr><th>Data Type</th><th>Description</th></tr>
<tr><td>D_GPS_Sat
D_GPS_Sensor
D_RadarSensor
D_LeddarSensor
D_PtCloud
T_Point
D_Xtype</td><td>The data structures (types) required for each senor type.</td></tr>
<tr><td>T_Sensor_Object_Global_Parameters</td><td>Provides the interface all the common data types for any given sensor, such as:
sensor status,
node ID within the domain / network,
time stamps (for system temporal alignment of each node)
sensor control messages,
sensor type information,
sensor name,
sensor parameters for data (e.g. cm, inches, tracks or point cloud etc.)
T_Sensor_Object_Control
The control data structures for sending control messages to a sensor, e.g. power on or off.</td></tr>
<tr><td>T_CivilianIdentityType_E</td><td>A GVA module designed to allow the system to send enum data types representing various civilian objects (e.g. people, bikes and buses / trucks etc.) to be fused.</td></tr>
<tr><td>T_SensorSpecificParamsType_E</td><td>Provides the sensor objects the ability to report their own specific parameters (e.g. measurement scales).</td></tr>
<tr><td>T_SensorSpecificType_E</td><td>Provides the senor objects the ability to report what type of sensor they are, GPS for example or Radar.</td></tr>
<tr><td>T_SensorStatusReportType_E</td><td>Allows the sensor objects to report errors in operation or give the system information regarding the sensor’s reading strength (in the case of light-based sensors such as the Leddar.</td></tr>
<tr><td>T_CommandRequestType_E</td><td>Provides the system the ability to send commands to a sensor to power off or on for example.</td></tr>
<tr><td>T_CommandResponseType_E</td><td>Allows the sensor object to respond to a command, i.e. command failed or was not recognised.</td></tr>
<tr><td>T_DateTimeType</td><td>The data type for time stamping consisting of nano seconds and seconds.</td></tr>
</table>

Figure 6.5 on the previous page also describes the sensor specific interface within the GSIA. It facilitates the transmission of raw sensor data to the GSFEA architecture supporting mode 1 of operation for the GSIA (Figure 6.14, page 159). It contains all the data types for multiple sensor types including a structure for an ‘unknown’ sensor type (using DDS extensible types which can be typed at runtime), that is, a sensor that the system hasn’t been pre-configured for. This structure was only modelled as a concept and not implemented within the GSFEA testbeds (presented within Chapter 7) as it didn’t provide any additional research impact. Table 6.6 provides a breakdown of the Sensor Specific Interface Modules (Figure 6.5).

Table 6.6 GSIA_Sensor_Specific_Interface module structure and description

GSIA_Sensor_Specific_Interface module		
DDS Topic Name	**Description**	**Code Snippet of Sensor Data to be Transmitted**
SO_GPS_Sensor	Provides the structures required for GPS sensor data. This is a simulated sensor sending fixed GPS data as can be seen within the C++ code snippet.	`SO_GPS_Sample->GPS_data().latitude(35);` `SO_GPS_Sample->GPS_data().altitude(25);`

SO_SRF	Provides the structures required for ultrasound sensor data. These are the physical sensors described within Sonic Range Finder Sensing Cluster (I2C), page 155.	`SO_SRF_Sample->SensorObject_Node_ID(nodeID);`
		`SO_SRF_Sample->sensor_details().sensorNode_ID(nodeID);`
		`SO_SRF_Sample->sensor_details().sensorType`
		`(GSFEA_Common::T_SensorSpecificType_E_def::SENSOR_TYPE__SO_SRF);`
		
		`SO_SRF_Sample->sensor_details().sensorParams`
		`(GSFEA_Common::T_SensorSpecificParamsType_E_def::SENSOR_PARAM__CENTIMETERS);`
		
		`SO_SRF_Sample->sensor_details().sensorStatusReport`
		`(GSFEA_Common::T_SensorStatusReportType_E_def::SENSOR_STATUS__STRONG);`

SO_RadarSensor	Provides the structures required for radar-based sensor data. This is a simulated sensor sending random data sets, generated within the C++ code snippet.	`SO_Radar_Sample->TracksData()[i].track_number(i);`
		`SO_Radar_Sample->TracksData()[i].distance(rand() % 100 + 1);`
		`SO_Radar_Sample->TracksData()[i].dopplerVelocity(rand() % 100 + 1);`
		`SO_Radar_Sample->TracksData()[i].theta(rand() % 100 + 1);`

SO_LeddarSensor	Provides the structures required for ledder-based sensor data. This is a CAN based sensor, sending real data, the details of which can be found within Leddar Sensor (CAN), page 152.	`SO_LeddarSample->SensorObject_Node_ID(nodeID);`
		`SO_LeddarSample->sensor_details().sensorNode_ID(nodeID);`
		`SO_LeddarSample->sensor_details().sensorType`
		`(GSFEA_Common::T_SensorSpecificType_E_def::SENSOR_TYPE__SO_LED);`
		
		`SO_LeddarSample->sensor_details().sensorParams`
		`(GSFEA_Common::T_SensorSpecificParamsType_E_def::SENSOR_PARAM__CENTIMETERS);`
		
		`SO_LeddarSample->sensor_details().sensorStatusReport`
		`(GSFEA_Common::T_SensorStatusReportType_E_def::SENSOR_STATUS__STRONG);`

SO_LidarSensor	Provides the structures required for lidar-based sensor data. This is a simulated sensor sending random data sets, generated within the C++ code snippet shown on the right.	`SO_Lidar_Sample->ptCloud().color()      = count % 255;`
		`SO_Lidar_Sample->ptCloud().count()      = GSFEA_Common::MAX_POINTS;`
		`SO_Lidar_Sample->ptCloud().intensity()  = (float) rand() / 1000;`
		`SO_Lidar_Sample->ptCloud().normal()     = (float) rand() / 1000;`
		`SO_Lidar_Sample->ptCloud().xLimits()[0] = (float) rand();`
		`SO_Lidar_Sample->ptCloud().xLimits()[1] = (float) rand();`
		`SO_Lidar_Sample->ptCloud().yLimits()[0] = (float) rand();`
		`SO_Lidar_Sample->ptCloud().yLimits()[1] = (float) rand();`
		`SO_Lidar_Sample->ptCloud().zLimits()[0] = (float) rand();`
		`SO_Lidar_Sample->ptCloud().zLimits()[1] = (float) rand();`

Figure 6.6 Sensor independent data model and tracked object lists, presented on the next page, describes the data model for the GSIA to provide operation in mode 2 (Figure 6.15, page 160). Allowing the sensor objects to complete basic fusion at the sensor level and only send objects lists to be fused, further in the system, within the Capability Management Module (CMM) described later in this chapter (within section Capability Management Module, page 158). Additionally, this module also allows for a sensor independent approach to the integration of any given sensor technology.

The model described within Figure 6.6 provides the structure for the transmission of detected objects or tracks from any given sensor. Allowing the system to operate either at reduced functionality (but still provide some data) or in a constrained environment such as, when the architecture is implemented on a sUGV.

The GSIA Sensor Independent Interface provides a decoupling on the physical sensor to the rest of the system, allowing additional or future sensing technologies to be quickly integrated with the architecture. This also provides potential redundancy, if the sensor specific module was implemented physically separate from the rest of the system, and if a GSFEA systems failure occurred, sensor data would still be available to be transmitted. Table 6.7 provides a description of the GSIA sensor independent interface.

Table 6.7 GSIA Sensor Independent Interface module structure and description

GSIA_Sensor_Independent_Interface	
Topic Name	**Description**
SO_Sensor_Data	• Contains all the data structures required for sensor data collection in a generic form utilising the defined data structures within GSFEA_Common. • This provides the GSFEA with a decoupled generic approach to interfacing the architecture with a GVA compliant sensor fusion system (in this case the GSFEA).
SO_Tracked_ObjectList	• Provides the system with the ability to complete fusion at the sensor (edge fusion) and publish a sequence of object / objects to the CMM. • Provides the functionality for a hybrid approach to architecture topology whilst remaining GVA compliant.

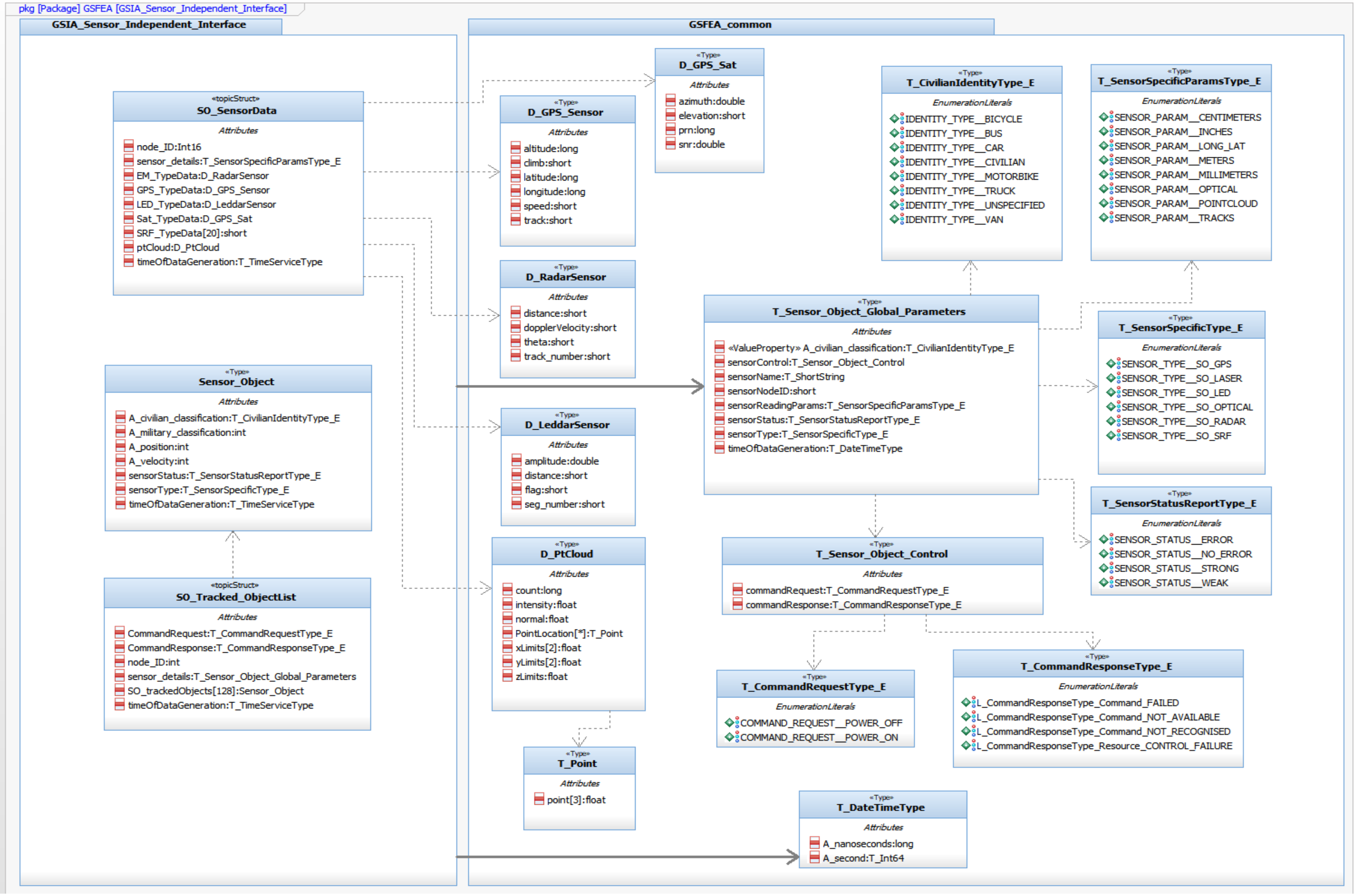


Figure 6.6 Sensor independent data model and tracked object lists

6.4.4 GSIA running demonstrator implementation

For the processing requirements of the GSIA a BeagleBone Black processing unit has been used to represent an embedded COTS solution for sensor interface processing. The sensor specific module is interchangeable and provides the sensor independent module with relevant data model structures on the GVA facing side of the bridge whilst supporting the sensing technology data structures on the sensor facing side of the module.

Physical sensors, buses and relevant models

The following figure (Figure 6.7) describes how a data model of the ISO 11898-2,3 and 7 has been created to provide the harmonisation of these standards with the DefStan 23-009 GVA, with a practical demonstration of the proposed architecture to communicate with a Leddar M16 sensor. Unlike the work completed here [107] around the same time this research was being conducted, the paper does state that the CAN messages are mapped to the NGVA Data model for the automotive sub-systems, however, currently there is no such module in any published NGVA data models (currently version 1.0 found here [108]).

Therefore, a model has been created to be GVA compatible to provide an automotive interface for CAN messaging within the GVA via the legacy system gateway discussed in Figure 6.3 Simplified GVA data infrastructure [18].

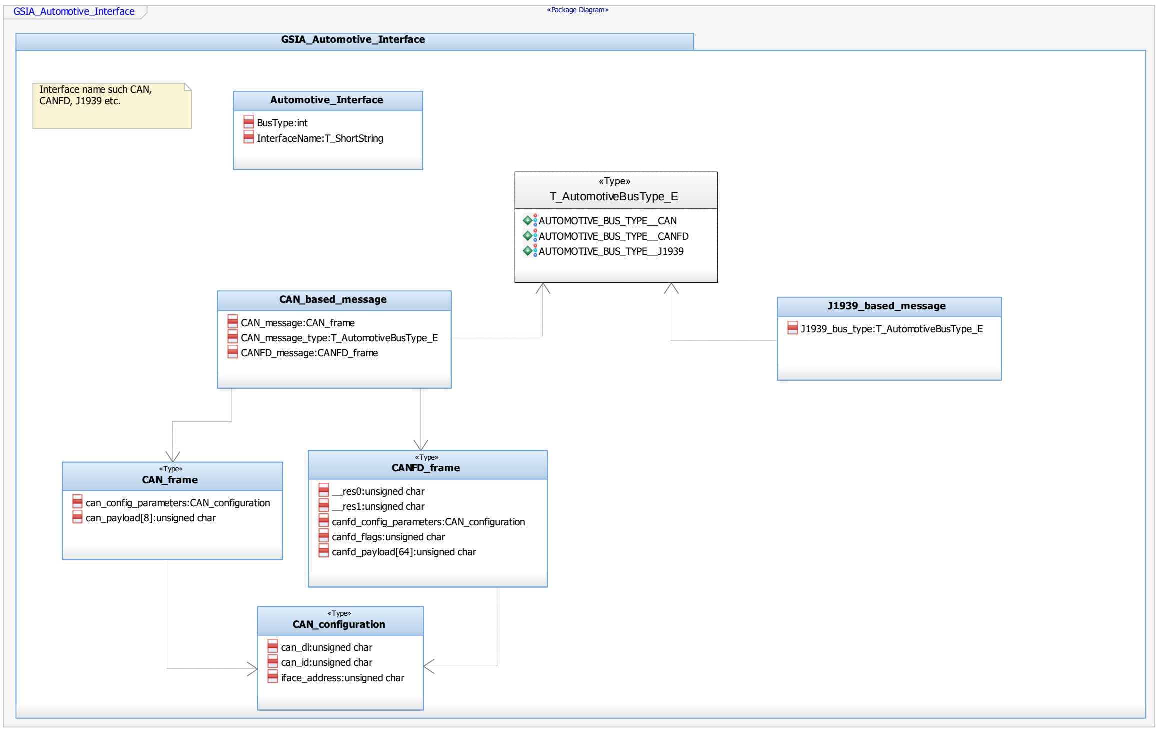


Figure 6.7 GSIA automotive interface CAN model

Leddar Sensor (CAN)

The evaluation Leddar sensor from LeddarTech (Figure 6.8) is a low-resolution IR LED sensor that can detect, locate and measure objects in a specific Field of View (FoV). This sensor has a detection range of up to 50 metres and 45° beam width FoV made of 16 independent channels (shown in Figure 6.9). The sensor supports the simultaneous acquisition and detection of multiple objects. The sensor module provides USB, RS-485 and CAN interfaces.

Figure 6.8 Leddar sensor

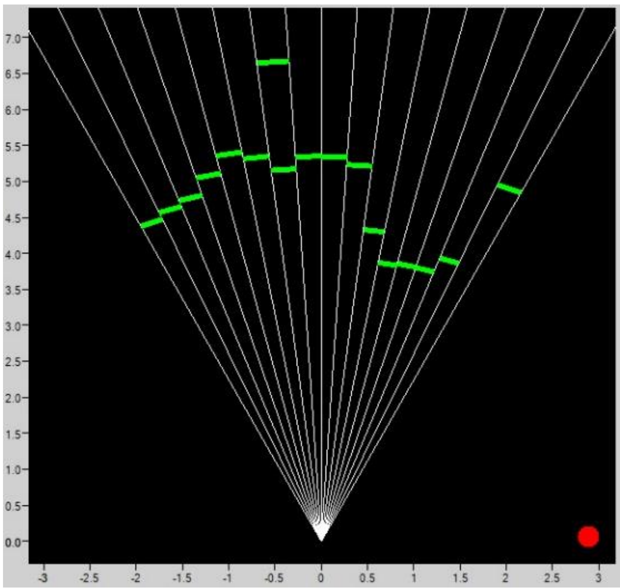


Figure 6.9 Leddar sensor output visualisation

Figure 6.10 on the following page, present the GSIA approach for Controller Area Network (CAN).

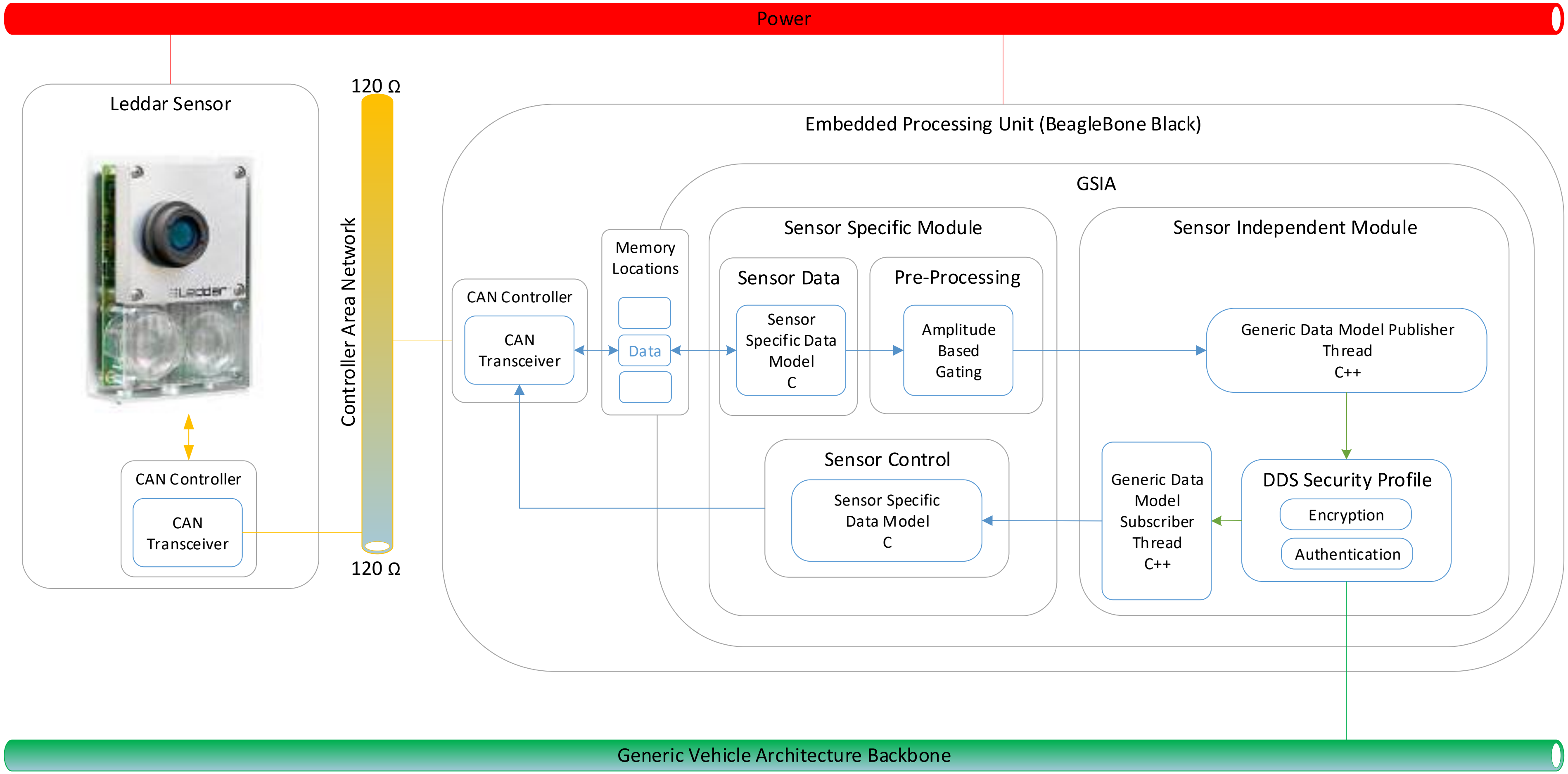


Figure 6.10 Controller Area Network (CAN) Generic Sensor Interface Architecture

The Controller Area Network (CAN) Generic Sensor Interface Architecture (Figure 6.10 on the previous page) describes the implementation of the GSIA on a BeagleBone Black coupled with the Leddar sensor. The implementation of the GSIA module consists of the following (Table 6.8 below).

Table 6.8 Implementation details of the GSIA module shown in Figure 6.10 for CAN Integration

GSIA Implementation Details (CAN bus)	
Physical and Logical Components	**Description**
Physical	• The Leddar sensor itself and the CAN bus, • The CAN controller within the BeagelBone Black, • The power bus and the data bus (Ethernet).
Logical	• Memory locations within the BeagelBone Black where data is stored and retrieved with C pointers.
Sensor Specific Module (logical)	• This module allows for the decoupling of the physical sensors specific data structures from the rest of the system, • The C / C++ program for collecting the sensor data (Sensor Data Module), C++ code for pre-processing that then passes the data to the Sensor Independent Module (this can be via shared memory with DDS or simply including both data models within the same program, allowing the data structures to be available to each other), • The sensor specific data structures are also available within the C / C++ program running here ready to collect and send commands to the sensor back over the CAN bus using the AutomotiveInterfacePSM.
Sensor Independent Module (logical)	• The collected data passed from the sensor specific module is then transmitted over DDS via either the SO_SensorData topic or if the architecture is in edge fusion mode the SO_Tracked_ObjectList topic, • Data can also be published over DDS via the sensor specific module if required or if the GSFEA was damaged or failing for example. Therefore, supporting the potential for the crew to be provided with at least some useful basic sensor information, • In other words, if the sensor specific module was implemented physically separate from the rest of the system, if GSFEA systems failure occurred, sensor data could still be able to be transmitted, • The types for controlling the sensor are also available within the C / C++ program so that a DDS listener could be run to await commands for the sensor control.

Sonic Range Finder Sensing Cluster (I2C)

The sonic range finder (Figure 6.11) is typically used in car parking assist systems. The sensor can identify objects in close proximity (up to 6 metres) and is capable of determining the distance to the obstacle in the sonic field of view (Figure 6.12).

Figure 6.11 HC-SR04 sonic range finder [109]

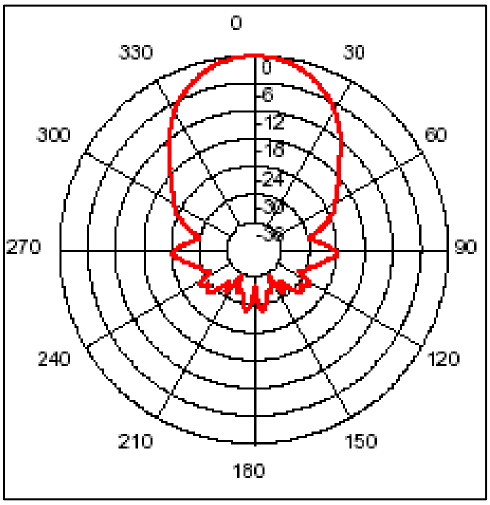


Figure 6.12 Ultrasonic sensor's field of view [110]

As with the Leddar sensor previously the implementation of the sonic range finding sensors is built with the BeagleBone Black platform. Figure 6.13 i2C Generic Sensor Interface Architecture on the following page, details the implementation and approach of the GSIA to integrate the sonic range finding type sensors.

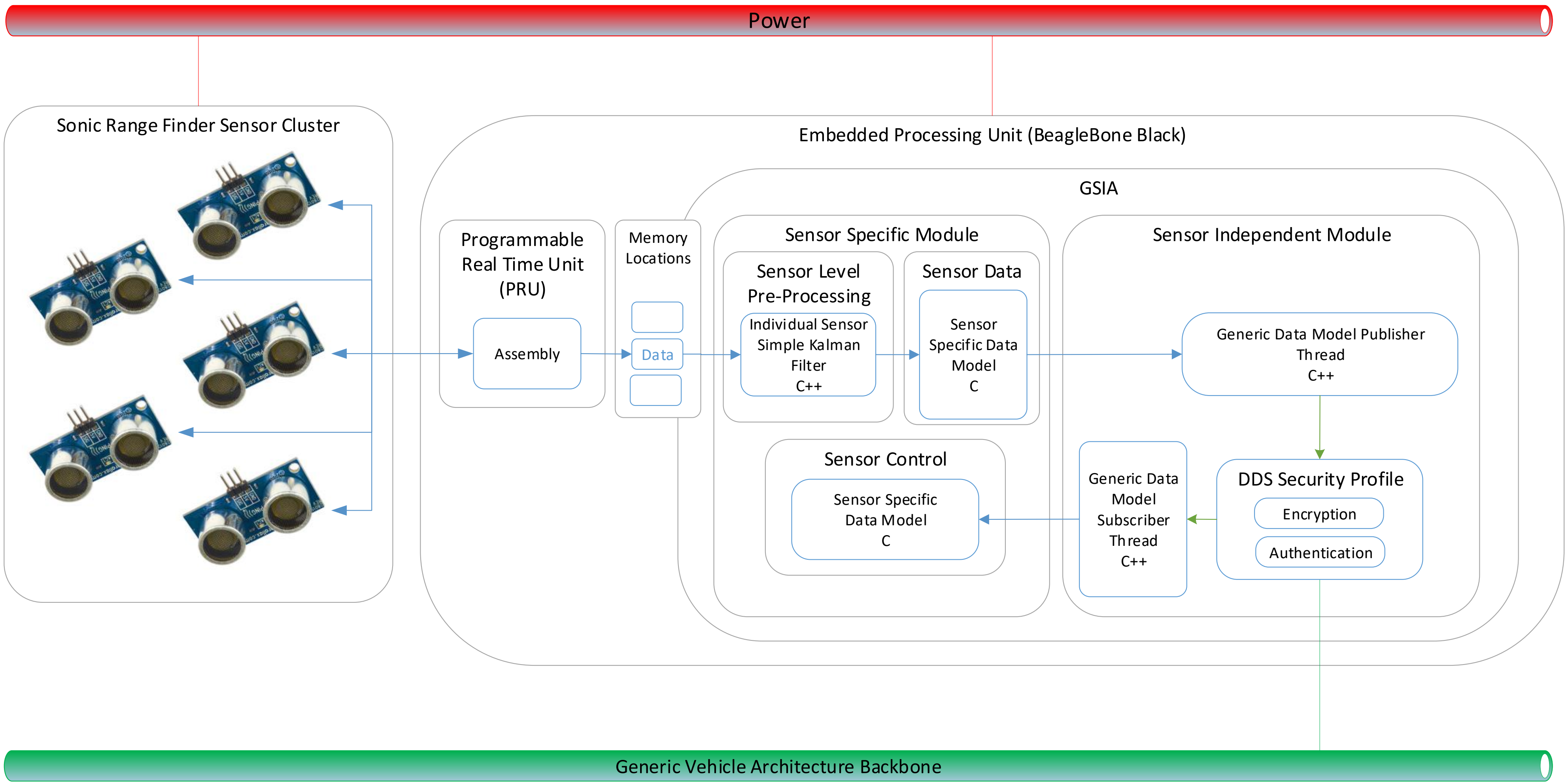


Figure 6.13 i2C Generic Sensor Interface Architecture

This implementation of the GSIA (from Figure 6.13 shown on the previous page) is presented within Table 6.9.

Table 6.9 Implementation description of the GSIA module shown in Figure 6.13 for I2C Integration

<table>
<tr><th colspan="2">GSIA Implementation Details (I2C bus)</th></tr>
<tr><th>Physical and Logical Components</th><th>Description</th></tr>
<tr><td>Physical components</td><td>The power and data buses,
x5 sonic range finding sensors,
The BeagleBone Blacks Programmable Real Time Unit (PRU),
This is a small 200MHz 32-bit processor that can be programmed in assembly and has no interrupts etc, just a small set of instructions (RISC). This was required due to the behaviour of the sonic range finding sensors. To retrieve a sensor reading the transducer sends out 40 pulses of sound waves and the transducer awaits an echo from these sound waves. One then calculates the distance an object is from the sensor by the time taken for the return echoes to be received taking into account the viscosity of the atmosphere the sound is travelling through. Therefore, when the sensor fired the thread must wait, measuring time (by clock cycles) without interruption by the OS scheduler, so that an accurate reading of the time taken can be retrieved.</td></tr>
<tr><td>Sensor Specific Module (logical)</td><td>Again, provides a decoupling of the sensor interface from the rest of the GVA compliant system,
This provides the ability for future updates to sensing technologies without having to add to the GVA data model, additionally, it also supports the multi-mode sensor fusion architecture.
The C / C++ program for collecting the sensor data (Sensor Data Module), C++ code for pre-processing that then passes the data to the Sensor Independent Module (this can be via shared memory with DDS or simply including both data models within the same program, allowing the data structures to be available to each other). A simple Kalman filter is applied here to reduce noise and error rate.</td></tr>
<tr><td>Sensor Independent Module (logical)</td><td>This module is exactly the same as the module presented previously within Figure 6.10 for Leddar sensor Generic Sensor Interface Architecture (GSIA).</td></tr>
</table>

6.5 Capability Management Module

Given that the ultimate goal for the integration of COTS sensing technologies is to provide as much modularity and upgradeability as possible; the notion of a fusion modality management module based on the work by Bish et al. [111] is presented in Figure 6.17. Further to the above, is the development of this novel paradigm as part of this research for the current architectural model proposed. One of the most cited constraints of sensor fusion electronic architecture is that each sensor fusion architecture is application specific [46] (designed and configured for a single vehicle type for example). Therefore, for the use cases described within the military context, being not for autonomous navigation it is proposed that a modular, reconfigurable sensor fusion architecture is feasible.

Several sensor fusion architectures exist. They utilise multiple sensor data sets and fuse them together to provide enhanced environmental awareness and informational precision to aid decision making [46-48]. Unfortunately, the current fusion process must be designed for the system it is required, then, fine-tuned to meet the requirements of the system. This is both costly and time consuming but more importantly prevents scalability or support for system changes.

A. Knoll et al. propose a partial solution to this problem [43, 49] by presenting a semi modular approach to the design of the sensor fusion architecture. However, their testing predominantly focused only on a single task (autonomous parking in this case) to demonstrate their approach. Moreover, only specific parts of their algorithm have the ability to be modular in design.

As stated by Elmenreich in previous chapters “For the future it would be advantageous to elaborate ways that provide inter-operation between components of existing fusion architectures instead of creating even more isolated systems anew.”[46].

With this in mind a common generic modular architectural approach is proposed that should, in theory, allow a single architecture design that could be used across multiple land systems (i.e. small UGVs, large UGVs, large manned combat systems).

Figure 6.14 and Figure 6.15 provided on the following pages presents the highest level of abstraction for the architecture proposed within this chapter. The design extends the research conducted by M. Aeberhard and N. Kaempchen and integrates the concept of an object list [112]. This is the idea that basic fusion can occur on the edge of the system (basically completing a simpler fusion process at the sensor itself then sending the results (in the form of an object list) forward to the Capability Management Module (CMM).

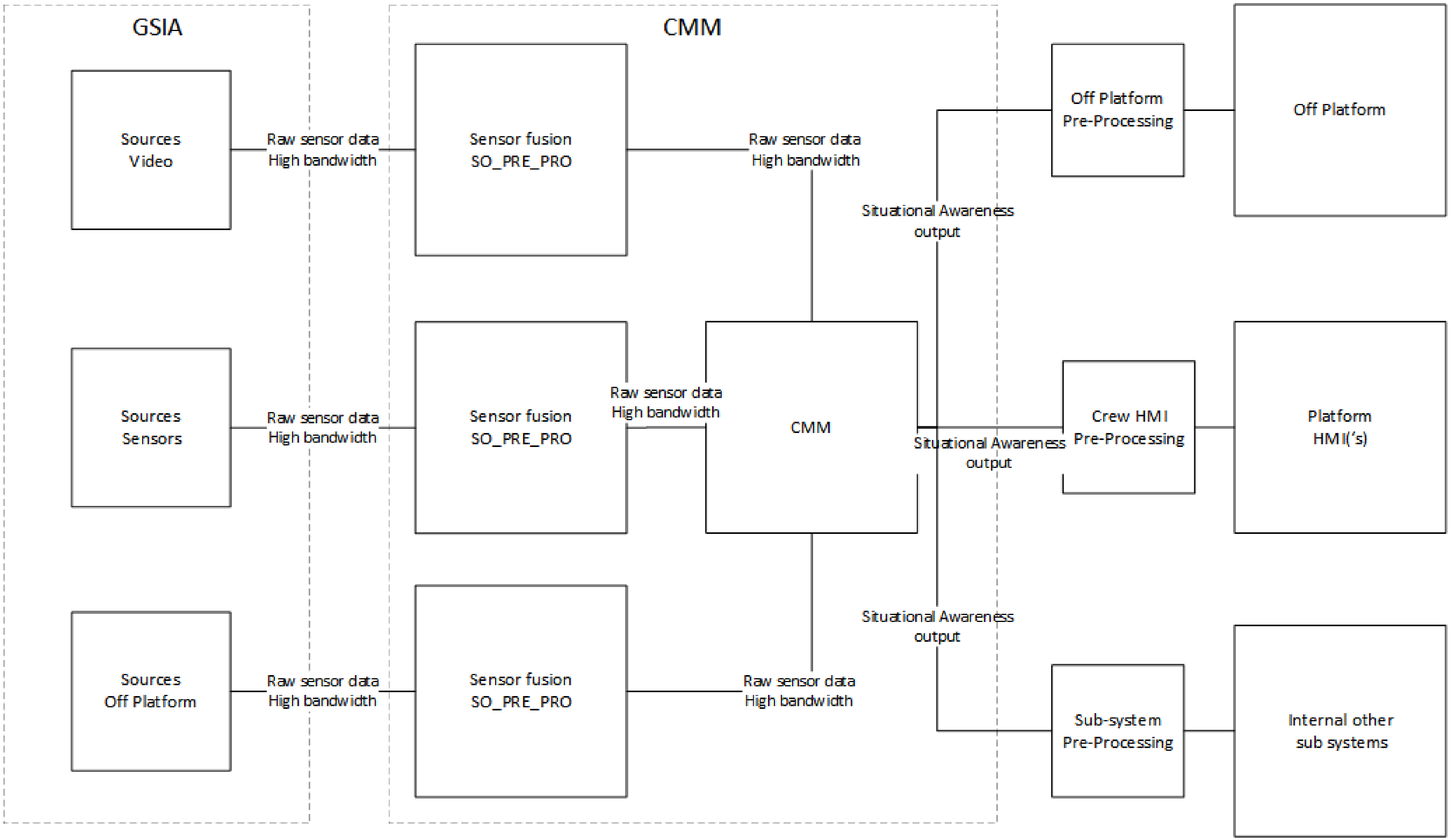


Figure 6.14 Mode 1, Multi-source hybrid design to support a common architectural approach

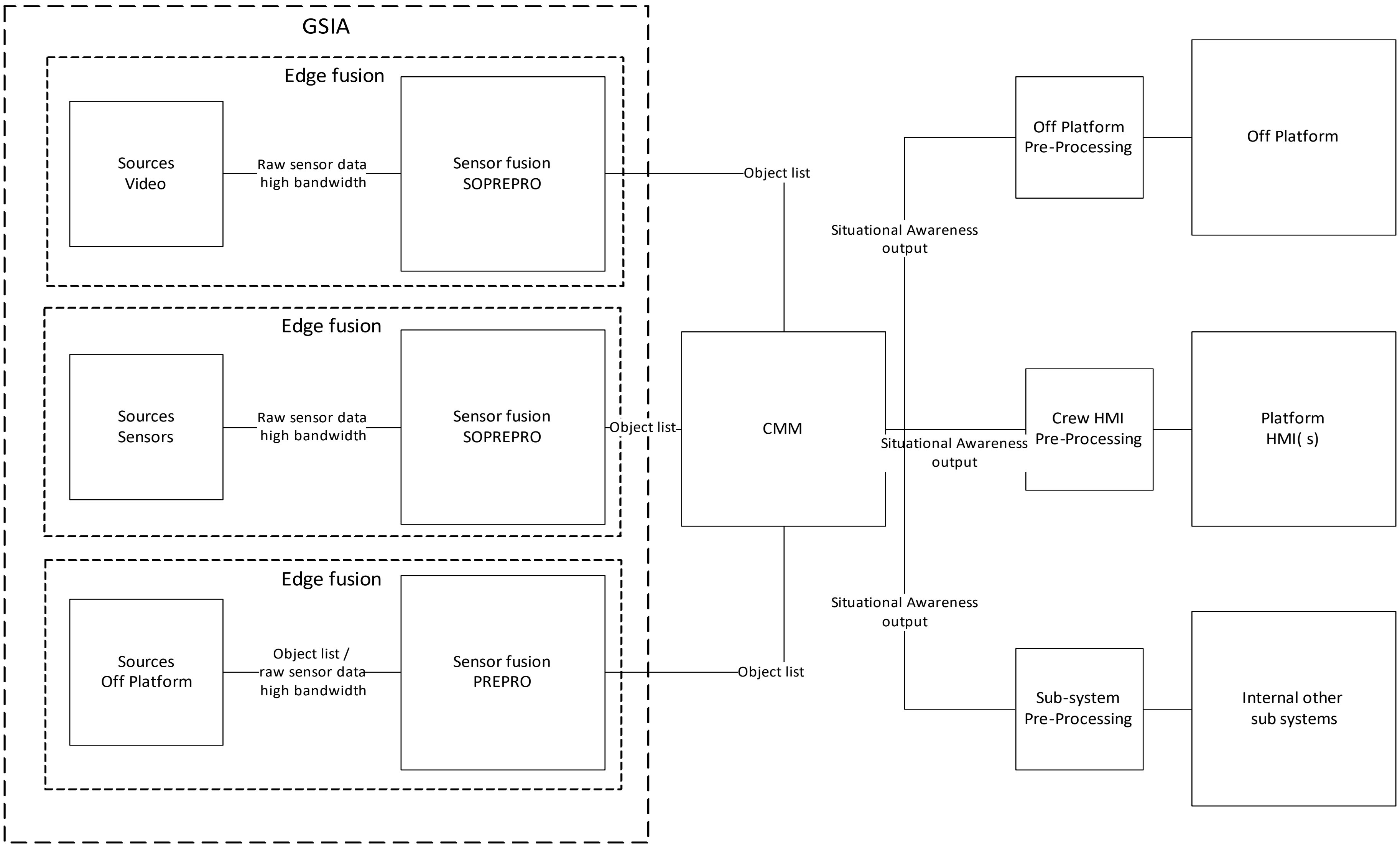


Figure 6.15 Mode 2, Multi-source hybrid design to support a common architectural approach

Figure 6.14 Mode 1, Multi-source hybrid design to support a common architectural approach, on page 159 describes how the sensor fusion architecture can perform in multiple modes of topology. Building on the work presented here [52] and extending it to develop a real time reconfigurable topology which is GVA compliant.

Figure 6.15 shows the different sensing technologies completing basic fusion at the sensor level (edge fused with Sensor Fusion PrePro being completed here) and then passing on an object list to the CMM to be further processed and fused. In our testbed demonstrator, SO_PrePro would be running on the BeagleBone Black sending object lists straight from the final output of the BeagleBone. In the opposite mode SO_PrePro would be running on a PC (for example). Figure 6.15 Mode 2, Multi-source hybrid design to support a common architectural approach on the previous page shows this difference between mode 1 and mode 2. This provides the sensor fusion architecture with a reconfigurable pre-processing module. Contained within this module could be a selection of or all of the common sensor data pre-processing functions, such as:

- **Filtering and prediction** – Here you would implement common algorithms such as the Kalman Filter to increase accuracy and or reduce error rate,
- **Local track management** – Algorithms for the management of associated tracks and observations,
- **Association** – Data association, basically associating the reading with a tracked object, e.g. for a moving object at T+1 is the sensor reading associated with the previous track at T+0,
- **Gating** – Here you would see algorithms or simple filtering removing sensor readings that are not valid, e.g. the Leddar sensor returns flags indicating the reflected light beam was too weak in strength to be a valid reading [113, 114].

Additionally, the architecture can of course support running any sensor in any mode depending on; Urgent Operational Requirements (UoR), system partial failure, damage and or being dependant on the land platforms processing capabilities (i.e. is it a larger Mounted Combat System or a sUGV).

Figure 6.16 GSFEA systems view presented on the next page describes the overall view of the architecture model that had been created using IBM Rational Rhapsody. We can see how all the modular components interact with each other. Essentially bringing together all the modules presented so far within this chapter. The Remote Land System Gateway has been omitted as it really would sit on the boundary of the proposed architecture.

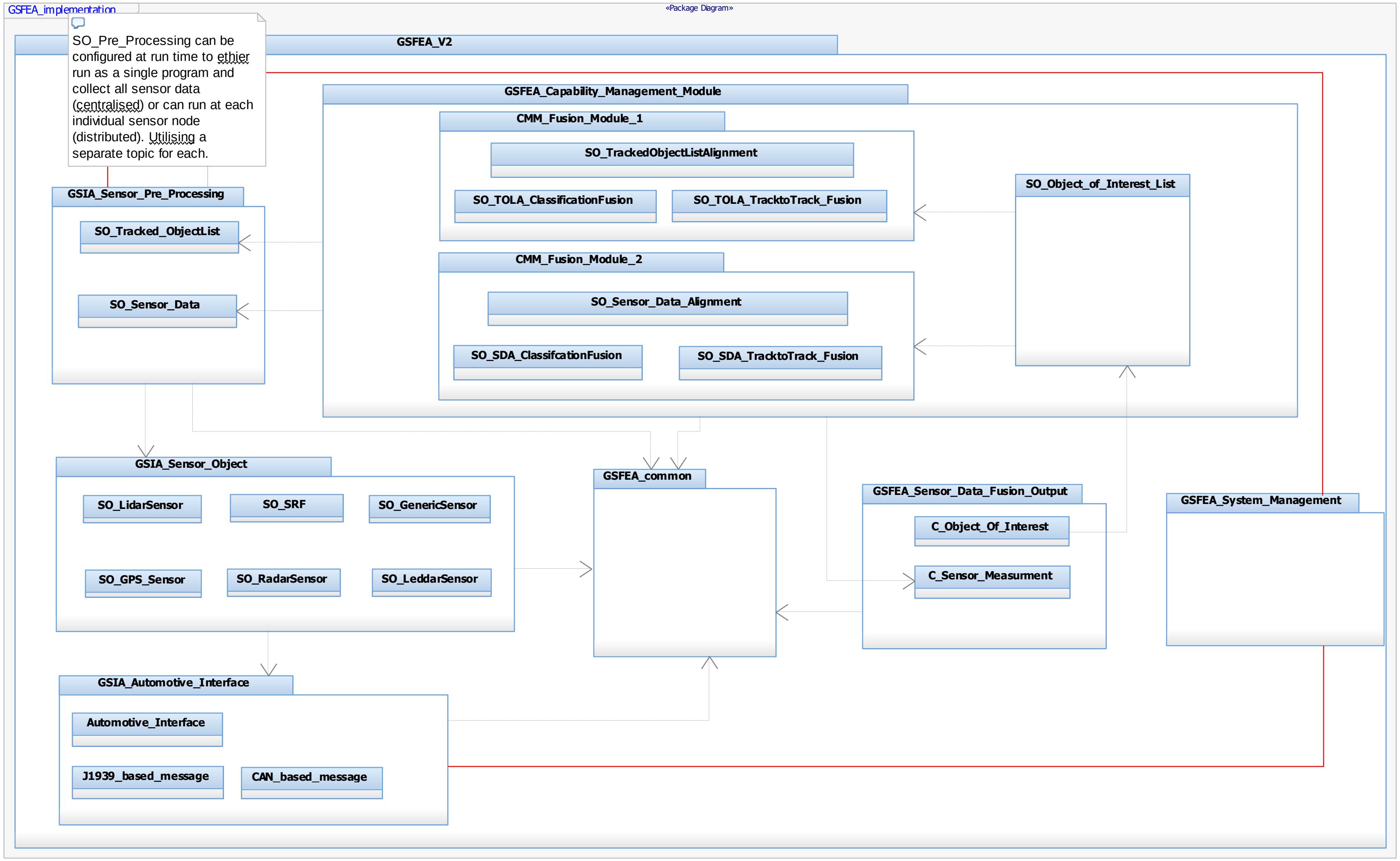


Figure 6.16 GSFEA systems view

6.5.1 Fusion Modality

The purpose of a CMM is to provide a base for the systems capability management, whilst also supporting cost effective upgrade paths, by allowing the fusion processes to be swapped, in real time, at any time (highlighted in Figure 6.17, below). Either during system operation or during upgrade cycles or with the addition of new sensing technologies without the need to change or upgrade the underlying supporting architecture. The reason being is that the above design allows fusion modules to be completely independent from each other. The overall fused output of the Modality Module will be based on the fusion of the active Fusion Modules. The Modality Module is the base of the system and would not require upgrading, the fusion algorithm here would not be sensor specific those tasks are allocated to the swappable Fusion Modules.

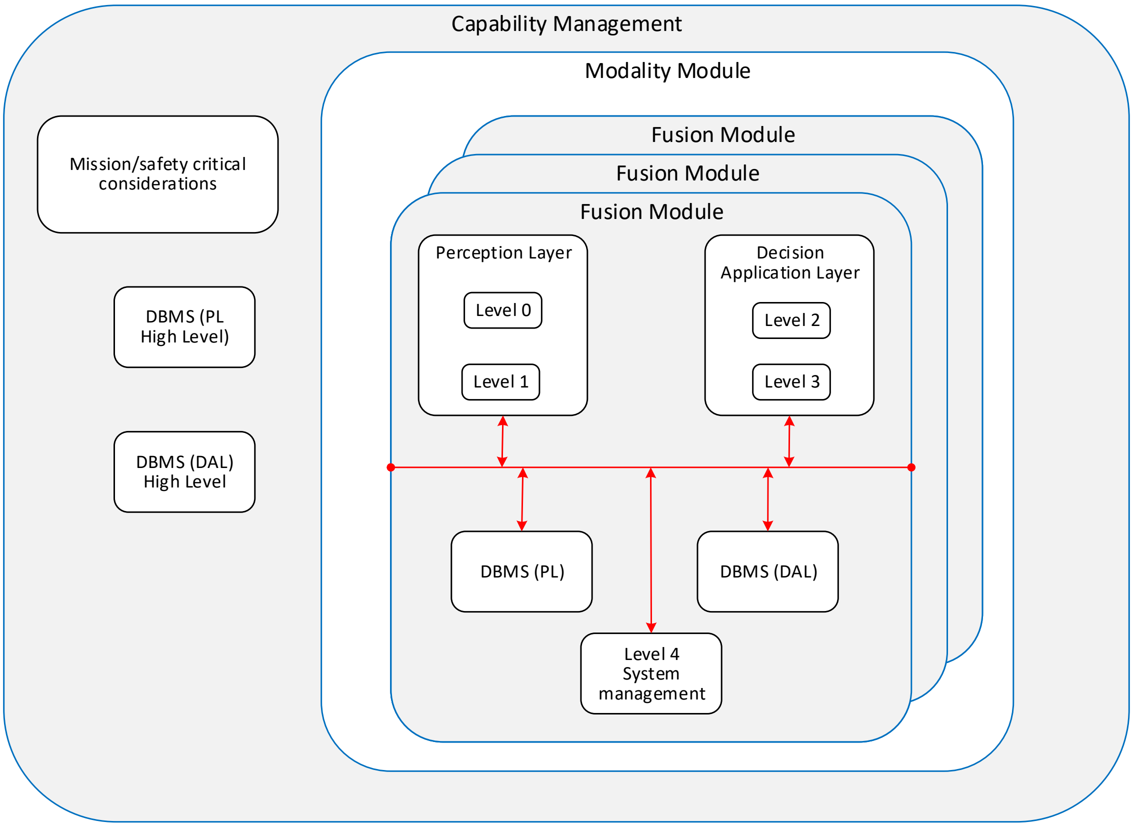


Figure 6.17 CMM logical architecture – detailed view

For example, through this module, the following can be supported:

- Remove sensors during upgrade and replace with new sensors, adding a newly developed fusion module to the list of modules available to the modality module,
- Ability to disable electromagnetic (EM) sensors such as radar but continue to use vision systems coupled with LiDAR or sonar range finder,
- Damaged sensors can be removed from the fusion process thereby removing the significant uncertainty they would produce within the fusion process.

The functionality of the CMM is illustrated by the use case diagram in Figure 6.18, with further details of implementation specific techniques can be found within section Fusion Modality Technique, page 164.

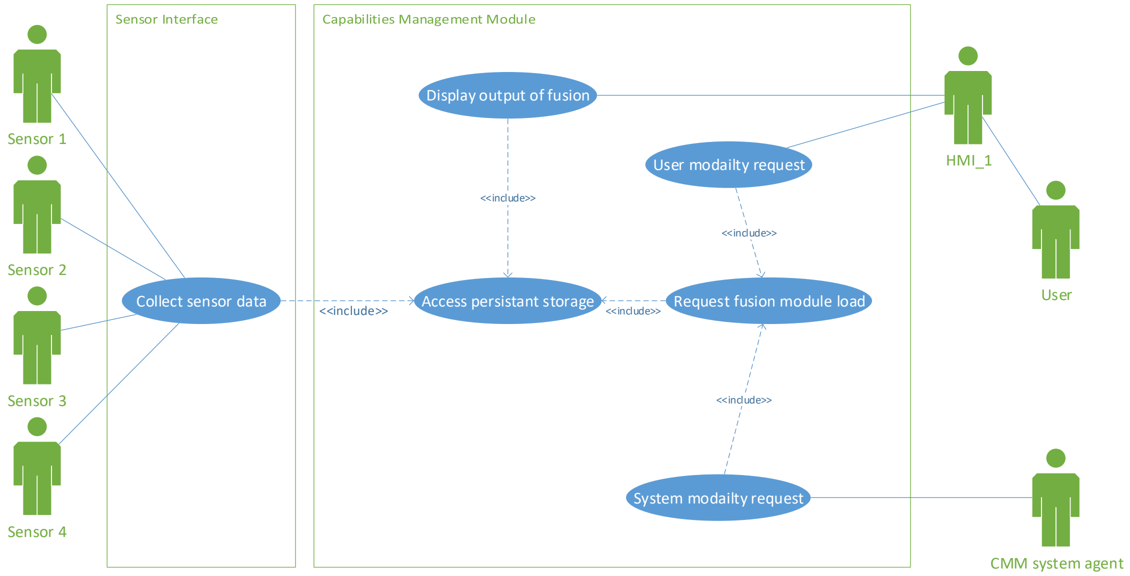


Figure 6.18 CMM high-level system use case

6.5.2 Fusion Modality Technique

To support the implementation of the independent 'swappable' Fusion Modules it would likely be worth investigating the atomic properties of the functional programming paradigm. Below presents a discussion as to why this may be of interest, given that the independent modules are also atomic in nature.

A brief analysis has been carried out to define or dispose of any potential benefits or constraints of utilising the functional programming paradigm for (primarily the design process for a functional language) could offer many benefits here. The idea of another module here residing within the Capabilities Management Module (CMM) that is an atomic structure housing all the current loaded fusion modules is worthy of further attention.

Of particular interest is the analysis of core behaviours of the functional paradigm coupled with a study of the methodology used to design a fully functional core process. It is envisaged that each fusion algorithm whilst perhaps following an OO approach and structure could be treated as a functional programming method by the CMM's internal module for loading and unloading fusion modules.

The behaviour of these fusion modules can be irrelevant to this internal module, their Input/output (IO) is all that is important. Utilising a functional programming paradigm in the design of this module's architecture promotes not only modularity but also offers true parallelism if the design strictly follows the functional paradigm. This would require further investigation and is currently outside the scope of this body of work.

6.5.3 GSFEA Data Management and Alignment

One central requirement to any sensor fusion implementation is the temporal and spatial alignment of all nodes and or sensors / sensor data within the system, as described within Chapter 3. The GVA / NGVA standards already provide a robust coordinate management system, therefore, it has not been considered here, the GVA and NGVA coordinate system ([33, 108]) is capable of providing the necessary spatial requirements for the GSFEA.

However, the temporal alignment solutions within Def Stan 23-009 and the NGVA STANAGS are not robust enough for a sensor fusion sub-system (currently NTP based precision). Therefore, the use of IEEE 1588 Precision Time Protocol (PTP) has been recommended and implemented within the GSFEA testbed / Demonstrator. The following sub-section presents this selection of temporal system alignment in a little more detail.

6.5.4 IEEE1588 Precision Time Protocol Implementation within GSFEA

To achieve temporal alignment of messages (critical to sensor fusion techniques) IEEE 1588 – 2008 Precision Time Protocol (PTP) [115] was used across all testbeds. This was also used within the demonstrator / testbed experiments to synchronise all hardware clocks across all nodes. Given that PTP has a precision down to the 10s of nanoseconds makes this technology much more closely aligned with the requirements of a real time, publish, subscribe based sensor fusion sub-system. The impact of utilising PTP on the same network as the DDS data will be assessed within Chapter 7 Generic Sensor Fusion Electronic Architecture Testbed.

6.6 Land Systems Remote Gateway

A final core component for achieving land systems integration with future Internet Of Battlefield Things (IOBT) is the management of the remote connection between land systems and off platform systems / vehicles or other LOSA infrastructure. A core requirement is to have a gateway between the land platforms sub-systems and the off-platform communication channels, providing authentication and security for the internal land platform sub-systems.

To achieve this, a conceptual model for a Land Systems Remote Gateway (LSRG) is presented. The following sections present basic requirements analysis for this gateway, highlighting the core components.

The design is intended to offer support for off-platform communication as described in the operational view presented within Chapter 4, 4.1.1 Proposed Operational Concept for Military Land Platforms, Figure 4.1 Operational view of proposed system (current / future), page 74.

6.6.1 LSRG User Requirements

The user requirements (UR) provided below (Table 6.10) present the stakeholders' high-level requirements for the off-platform gateway.

Table 6.10 LSRG user requirements

REQ ID	Initial Requirements Table
	User requirements
UR1001	The LSRG should comply with relevant Defence Standards.
UR1002	All communication protocols, message formats and ports should be based on open standards whenever possible.
UR1003	The LSRG must incorporate a DDS (Data Distribution Service) component/interface.
UR1004	The LSRG architecture shall be adaptable to different land platform configurations.
UR1005	THE LSRG must provide full control over a remote connection off platform to at least one other LSRG.
UR1006	The LSRG should be able to operate independently from all other vehicle sub-systems.
UR1007	The LSRG should support wired and wireless connections

6.6.2 Architectural Requirements

The following, Table 6.11, presents the expansion of the user requirements shown above (Table 6.10) to develop the initial architectural requirements for the LSRG.

Table 6.11 LSRG architectural requirements

REQ ID	Initial Requirements Table
	Architectural requirements
AR1001	The LSRG should provide HUMS data related to the communication channel currently available (link speeds, connection type (e.g. wireless, wired).
AR1002	The LSRG shall comply with DefStan 00-082.
AR1003	The LSRG shall comply with DefStan 23-009.
AR1004	All communications to off-platform land systems should pass through the LSRG.
AR1005	The LSRG must support bi-directional communication.
AR1006	The LSRG must support data encryption.
AR1007	The LSRG must support connection authentication.

6.6.3 System Requirements

Table 6.12, provides the basic system requirements for the LSRG.

Table 6.12 LSRG system requirements

REQ ID	Initial Requirements Table
	System requirements
SR1001	The LSRG must have a dedicated battery/power source.
SR1002	The LSRG dedicated power source must provide power for a minimum of 6 hours when activated.
SR1003	The LSRG must additionally support being powered externally through the communications interface.
SR1004	The LSRG should support video encoding to reduce video bandwidth usage.
SR1005	The LSRG should support video decoding to reduce video bandwidth usage.
SR1006	The LSRG could support operating in ‘recovery mode’
SR1007	The LSRG should provide a DDS Secure V1.0 profile.
SR1008	The LSRG must support operating in ‘being recovered mode’

Figure 6.19 on the following page presents the conceptual architectural components of a proposed Land System Remote Gateway supporting OMG DDS Secure V1.0.

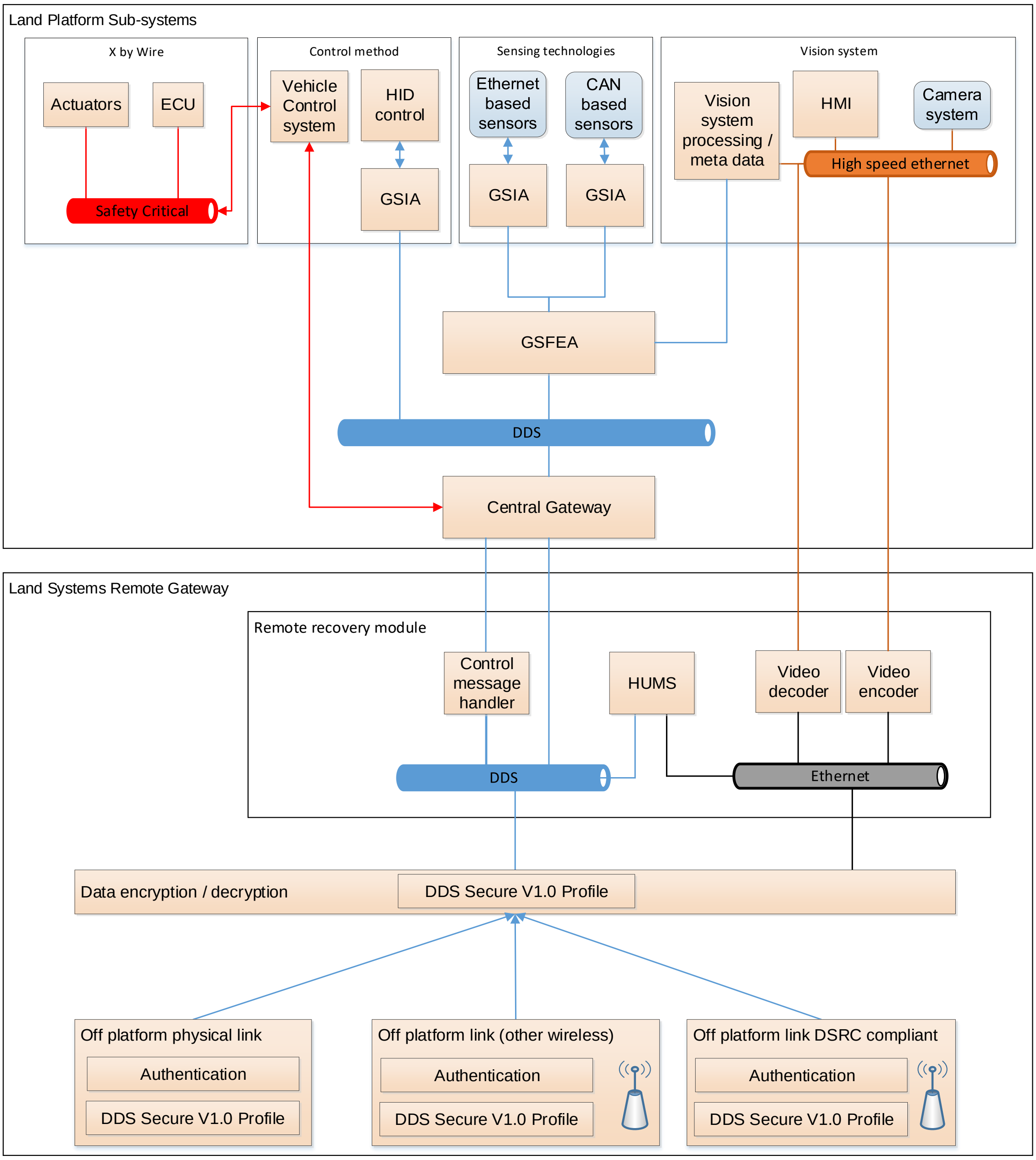


Figure 6.19 Land Systems Remote Gateway (LSRG)

The following sections contain a breakdown of each component shown in Figure 6.19 above.

6.6.4 Land Platform Sub-systems

X-by-Wire

This component represents the vehicle's X-by-Wire sub-systems and is connected to the physical control systems (steering wheel, brake pedal etc). Messages can also be sent to the sub-system gateway.

Control Method

This component details two methods for controlling the X-by-Wire sub-system. Remote operation of X-by-Wire systems could be controlled by an operator through a terminal with a Human Interface Device (HID) as the control method. Utilising on board vision systems to enable short distance indirect driving (e.g. to pilot the remote land platform after the initial assessment and relocating the land platform near the recovery platform for towing/recovery).

However, it may also be relevant to support the recovery vehicles physical controls to remotely operate another land platform, thus, allowing crews members who may have not received training for operating sUGV / UAV or damage has occurred to any other control systems (HID device input/HMI for example.), therefore increasing redundancy.

The components within this module are as follows:

- **Vehicle Control System** – This represents the typical physical components of a vehicle control system (e.g. steering wheel, brake, accelerator and clutch pedals etc),
- **HID Control –** It is expected that for remote operation of X-by-Wire sub-systems a HID device with an HMI is appropriate.

It is also expected that the central gateway would handle the adaption of messages from the HID to safety critical messages for control over the X-by-Wire systems through the control message handler.

Sensing technologies

Represented here is a selection of sensing technologies and communication types. This module is an example of many of the COTS sensing technologies investigated within this report with any other additional sensing technologies that may be available.

Vision System

This describes components of internal/external vision systems that could be found within military land platforms. The vision system processing module is responsible for processing image data and creating meaningful information such as object recognition/identification and so on.

GSIA

The GSIA is responsible for the conversion of COTS sensing technologies communication protocols to GVA compliant DDS messages for consumption by other sub-systems. As demonstrated within the VRC WP 3 testbed (e.g. the GVA compliant sensor interfaces and the remote HID GVA compliant interface). Described within Chapter 6, 6.4 Generic Sensor Interface Architecture, page 143.

GSFEA

This represents the sensor fusion architecture described within this Chapter (6 Generic Sensor Fusion Electronic Architecture, page 135.

Central Gateway

A common platform gateway separating and or converting different types of communication protocols and messages from multiple sub-systems to provide availability of data or messages to between sub-systems. Segmentation of processing and memory would occur here (using hypervisor technologies for example).

6.6.5 Land Systems Remote Gateway

This module would be responsible for the initial authentication of connections as well as any data encryption methods being used. This module serves as a barrier between the internal sub-systems of a land platform and external communications to other land platforms.

Remote Recovery Module

The module was designed as per the research requested by the UK MoD, under investigation was the premise of being able to interact with a land system that had been disabled on the battlefield.

Control Message Handler

Provides message formatting support for the central platform gateway, depending on control method selected (e.g. vehicles physical controls, HID device/HMI).

HUMS

Provides necessary HUMS data to other sub-systems or the operator, for example:

- Communication link strength (if wireless),
- Bandwidth available,
- Is safe indirect driving available across current link due to bandwidth (safety parameters would be decided upon beforehand),
- General gateway operational status.

Video Encoder

This module is responsible for encoding (compressing) raw video data from the vision system to other formats suitable for transmission at a reduced data rate, therefore decreasing bandwidth usage.

Video Decoder

This module is reasonable for decoding (decompressing) video data back to its original state not only, so the operator can view the higher quality images but more over for the vision systems processing module to be able to provide any object detection/recognition (usually these types of systems/algorithms offer higher performance/accuracy when using raw video).

Data encryption/decryption

Manages the encryption of messages; feasibly this would contain a DDS Security profile applicable to the functions of the LSRG, allowing encryption of outgoing messages and the decryption of incoming messages.

External Communication Links

The modules contained here represent all supported communications links off the platform and act as the barrier to the internal sub-systems of a platform by performing authentication of users/connections, DDS domain access, topics publish and subscribe access rights.

6.7 Securing COTS Sensing Technologies Within MCS

As noted within the previous Chapter (Chapter 2, Data Management and Security within DefStan 23-009 Part 1: Infrastructure) securing COTS technologies is a critical obstacle to integration and is a core component for the sensor interface architecture.

Intrinsically many COTS technologies have publicly available data sheets regarding their communication message structure and other operating parameters. It is considered a strong benefit to the security of the GVA environment when integrating COTS technologies to be able to secure network nodes and DDS topics using the OMG's DDS-Security Version 1.0 (implemented within RTI's Connext DDS Professional).

This public information could provide attack vectors for possible malicious network manipulation through the node interface such as:

- **Unauthorised subscription to DDS topics** – A malicious node subscribes to a topic and consumes data and derives vital information from system/sub-system (e.g. an attacker has placed a node externally on the vehicle and begins retrieving vehicles localisation data),
- **Unauthorised publishing of data** – A malicious node publishes to a topic and attempts to corrupt vehicle data (e.g. an attacker attaches a node to the platform via an external sensor interface and begins publishing incorrect sensor data),

- **Unauthorised domain participant** – A malicious node could join a domain and attempt to subscribe to as many topics as possible silently retrieving as much system data as possible. This could then be used to either publish malicious data (once the system had been analysed) or continue to silently subscribe to platform data to gain tactical advantage.

The following sections present a breakdown of OMG DDS security specification V1.0, which could be used for securing data transfer between various sub-systems as well as providing access control to prevent malicious nodes from even joining the DDS domain. It is also feasible that OMG DDS security specification could support detection of intrusion attempts (using the live security logs). Thus, allowing interfaces to be physically powered down for example, to prevent network interaction between a node and the rest of the physical network/communication system.

6.7.1 OMG DDS Security Specification V1.0

In September 2016, the OMG formally released their security specification V1.0, containing significant, functional security specifications for DDS. RTI, Open Splice contributed to the development of the standard and during 2017 released their first implementations of the DDS secure specification [94].

The specification is implemented within the middleware layer through a series of plugins; Figure 6.20 OMG DDS Security Architecture Overview describes the interactions between the various modules within the DDS system.

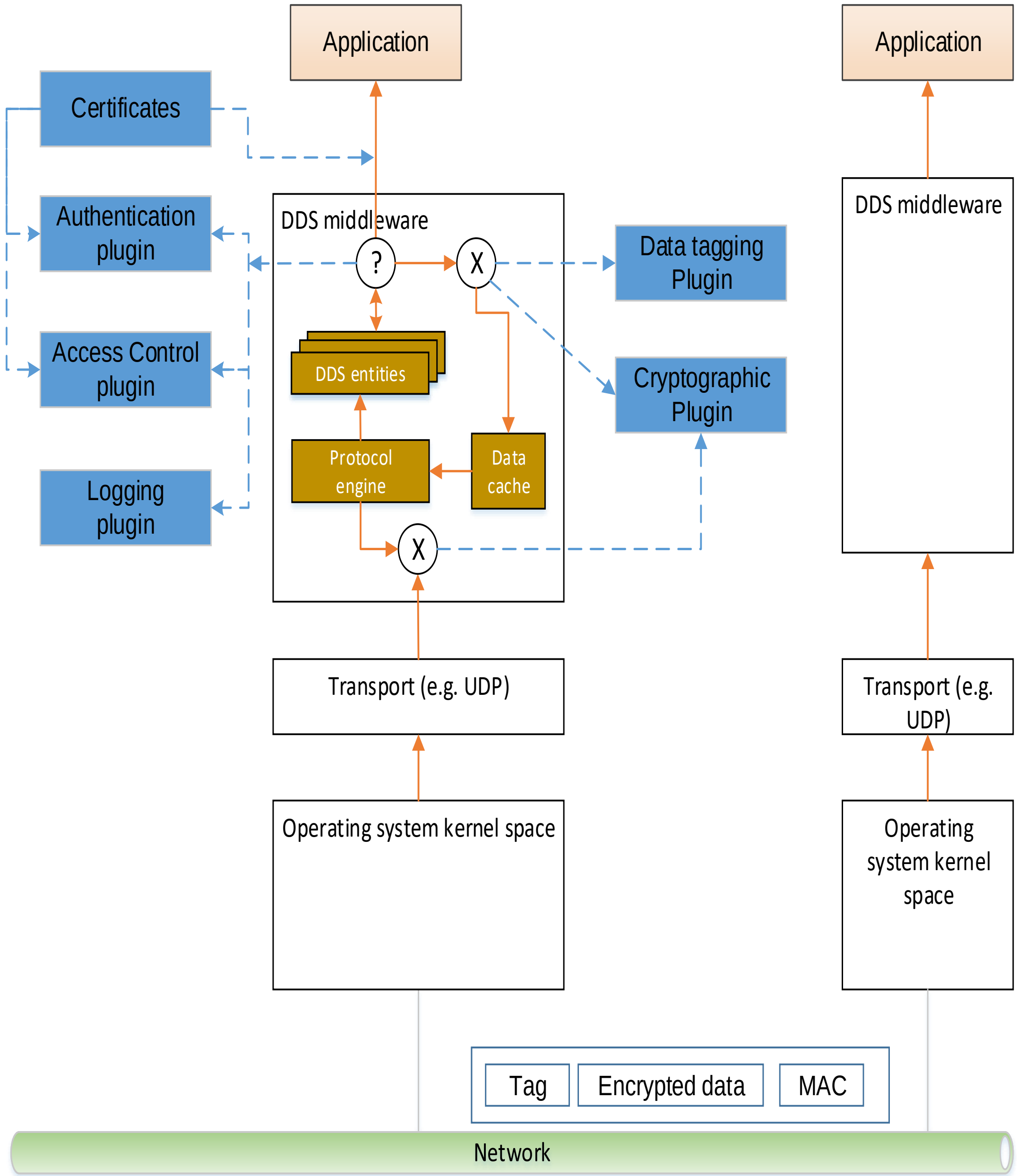


Figure 6.20 OMG DDS Security Architecture Overview (based on [94])

A brief overview of the current specification and the current capabilities offered are described within Table 6.13 on the following page.

The DDS security specification provides the following high-level security features as described within Table 6.13.

Table 6.13 OMG DDS Security Specification High Level Features

Plugin Name	Description
Authentication plugin	Supports the ability to authenticate all domain participants/users that intend to invoke operations over DDS.
Access control plugin	Provides control over all aspects of the DDS domain, including: • Topics publish and subscribe privileges (which topics can match with each other), in other words which domain participants can publish or subscribe to any given topic, • Which participants can join which domain.
Cryptographic plugin	Provides the encryption and decryption operations, the middleware invokes the chosen encryption technology/algorithm (e.g. open secure socket layer (openSSL)).
Logging plugin	This provides data logging of all security related events, such as an unauthorised attempt to join a domain or read a topic.
Data tagging plugin	Allows for data tags to be added to DDS messages this could provide additional access control (access could be granted based on the tag) or add meta data regarding a message such as message priority (e.g. for use by an intelligent digital assistant to understand data). Tagging would only be used by applications implementing DDS and is not used by the middleware itself. However, a similar capability can be implemented by including this data as a member of the original DDS message.

Currently all major vendors (RTI, Open Splice, Twin Oaks) support OMG DDS Secure V1.0, this specification is considered a robust solution for securing COTS sensing technologies. This is considered to be a critical component to take advantage of for enabling COTS sensing technologies integration/harmonisation within the GVA environment.

6.7.2 Securing PTP integration

Whilst IEEE 1588 PTP has been implemented on all nodes within the testbed / demonstrator, under consideration but not implemented is a method for securing the PTP daemon. Given that temporal alignment between all nodes is critical for sensor fusion [46, 116, 117]. Figure 6.21 below describes one possible method for securing the PTP daemon start / stop operation, and monitoring of any given node within the GSFEA.

Whilst this has not been implemented and is out of the scope of this body of work, it has been considered as a requirement for a sensor fusion architecture designed to operate within the GVA environment. Def Stan 23-009 currently utilises Network Time Protocol (NTP) as discussed earlier within this chapter.

Essentially, considering that the GVA / NGVA utilise DDS it makes sense that to control and manage PTP securely within the GSFEA, DDS and the security plugins specified within DDS should be the logical choice.

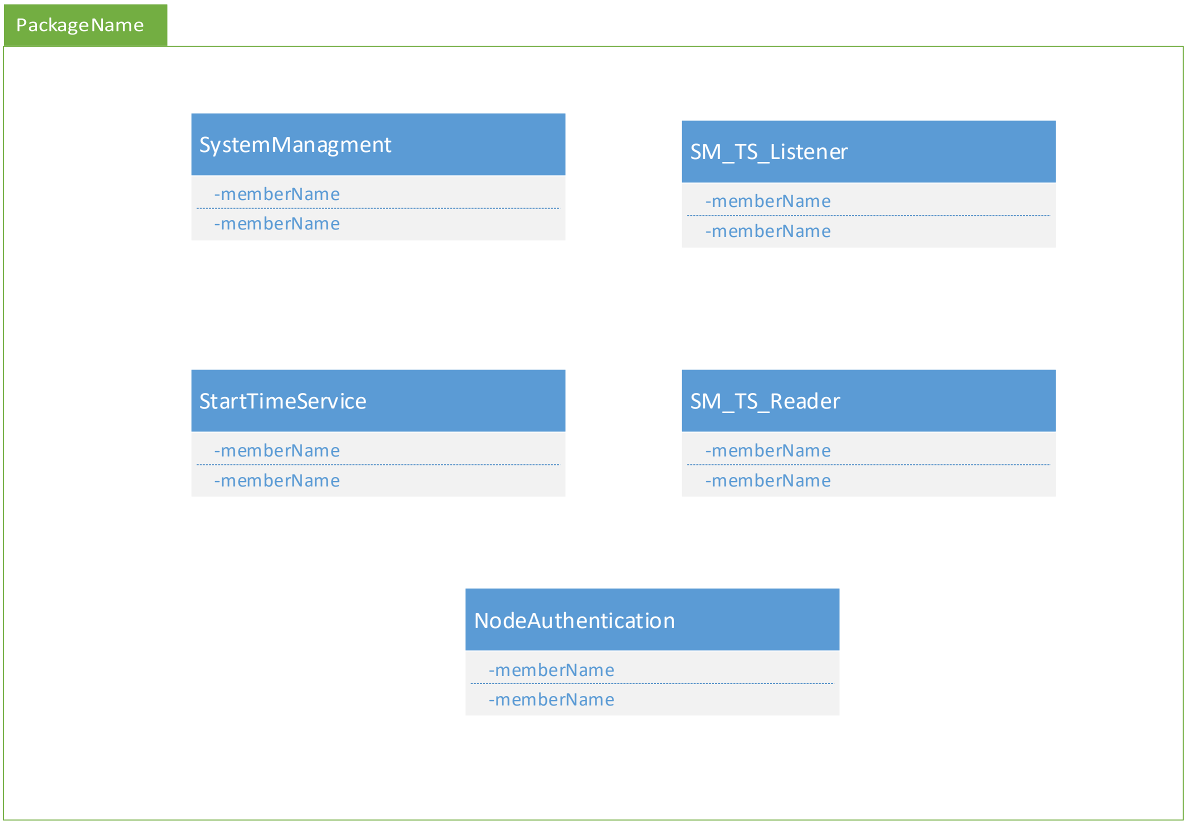


Figure 6.21 Securely start PTP Daemon

Using consistent security methods i.e. calling the daemon from within a DDS node designed specifically for running PTP.

This research is of course aware of other protocols for securing and encrypting data on the wire, such as IPsec, SECOPS (AUTOSAR), however, analysis of these protocols is out of the scope of this body of work, given the implementation of DDS secure.

6.8 System Management for Battlefield Environment

Given the operational environment, particular attention must be paid to the control mechanisms that provide the system with the ability to manage emissions from the sensors. That is, re-configuration of sensor environmental output (known, detectable or not, signal emissions) as needed.

This capability would provide the MCS with operational, scenario dependant modes such as EM silent operation (within the context of the technologies being discussed). So, depending on the current mission requirements such as reconnaissance it would be beneficial to be able to either severely reduce some sensor signal emissions or completely turn them off.

The capability to reduce sensor emission (such as low power mode for a range finding sensor, reducing detecting range and therefore emissions) is often sensor dependant (not all sensors provide the ability to reduce their range by reducing power to the sensor). Therefore, the architecture needs to support powering off/on sensor nodes; this in turn also provides the necessary platform power management features, for example:

- During events of peak power usage, i.e. active protection activation,
- To extend mission operational time at the cost of some or all sensing provided by the architecture.

This can be achieved through the use of the data model that would contain metadata regarding their sensor's current operational characteristics in terms of power management and therefore signal emissions output. This information would be sent along with the sensor data over DDS.

It is envisaged that this capability would be handled by the CMM and would be user controlled with the possibility of being system controlled also (in the event of sensor malfunction/damage for example). Of course, not all sensors provide a varying level of power management, therefore the only common option with many COTS sensing technologies is to simply allow the system to be able to deactivate and reactive them. Essentially turning them off and on without the crew having to dismount from the vehicle (that is, this operation can be HMI controlled).

It is also worth exploring as mentioned above, the implementation of some level of system autonomy with regards to the above capabilities. Given a situation where a sensor node or internal components of the system had become damaged for instance and emissions control no longer functioned as intended.

6.8.1 Safety and Security

One of the primary concerns with the integration and exploitation of sensing technologies within a MCS is the functional sensors' operational safety and security. Given the direction of this work and the current and future battlefield conditions, any exploitation of commercial sensing technology needs to carefully consider the operational behaviours and integration issues of these technologies, with regards to safety and security requirements.

The capabilities discussed within the previous Chapter overlap with the requirements discussed here. They provide the MCS with the ability to behave in a flexible manner given the emission control provided by the previous Chapters, which increases safety and security of the MCS during complex operations, where mission critical objectives may change over the course of the mission.

Safety

Primarily this section is concerned with the integrity of data/system, fault tolerance (graceful degradation), determinism and the systems interaction with the gateway module in contrast with performance metrics (MOP's), to provide an acceptable level of both performance and safety.

Whilst the proposed architecture currently utilises RTI's DDS implementation to transport messages throughout the system, it would be feasible to assume that in the future interaction could occur between the fusion core and other land platform systems. Some may be safety critical others may not. It is therefore expected that at a minimum, deterministic protocols would need to be considered within the interfaces to the gateway shown within Figure 6.19 Land Systems Remote Gateway (LSRG).

Currently the Object Management Group's (OMG) Data Distribution Service Interoperability wire protocol (DDSI) standard does not offer strict determinism (implemented within RTI's Connext DDS Professional). However, as discussed on the following page, the integration between DDS and Time Sensitive Networking (TSN) is under research as of 2019 to present and a prototype is already in place within RTI.

To fulfil further potential future requirements for a Generic Sensor Fusion architecture within the GVA environment, various safety protocols that offer some forms of determinism would be of considerable benefit.

The utilisation of deterministic protocols where possible/appropriate (i.e. Time Sensitive Networking (TSN) and DDS Integration). Deterministic protocols provide a strict guarantee that message transfer will be completed in a predetermined (during system design) time frame. For instance, a fire control system requirement may state that a message from the control input will always reach actuator control within 5 milliseconds.

Other considerations for safety would include:

- Redundancy (System Management Modules),
- Integration of Real Time Operating System (RTOS) providing a higher level of determinism at run time,
- Fault tolerance (i.e. graceful degradation. error checking and handling).

Security

Various security requirements would be necessary within a MCS sub-system such as the GSFEA. The following are a selection of basic examples that may need to be considered when developing a sensor fusion architecture for military land platforms in the future.

- Node Interface Security (considered a must have) – Encrypted frame/packet transfer (platform internal, node in-wards, IPsec etc.), node protection by utilising authentication before attaching new nodes to platform external interfaces, and time specific scheduling for removal of directed network attack vectors, such as ascending/descending sensor order or reads.
- System Security (access control) – User access control level for requesting system functions, for example, commander system control level and gunner system control level.

6.9 Conclusion

Described within this chapter was a novel solution to a modular, multi-mode (real-time reconfigurable topology), generic sensor fusion architecture design compatible with the Def Stan 23-009 GVA. The design described how it could be possible to have a common sensor fusion architecture for the land systems domain providing the through-life costs reduction approach inherent within the LOSA family of standards. Additionally, the GSFEA is middleware independent, supporting the generic approach to modelling design. However, it is expected that to achieve real time reconfigurability with other data transfer solutions may become complex to engineer.

The following chapter presents the results of implementing the architecture within various, diverse, testbed configurations. Primarily, latency measurements are presented taken from two different implementations of the testbed. One being a large UGV connected to the main network (highlighting worst case scenario for data transfer) and the other being a desktop version of the same testbed connected via a high-speed LAN (best case scenario for data transfer). The GSFEA proposed is analysed from a latency perspective against a DDS and CAN baseline measurement, additionally, the overhead of running PTP on the same network as sensor data traffic is also assessed and conclusions drawn.

7 Generic Sensor Fusion Electronic Architecture Testbed

7.1 Introduction

To evaluate the integration solutions presented within this thesis a diverse and complex DefStan 23-009 GVA compatible testbed environment has been developed. The benefit of developing a GVA compatible testbed is to support the rapid evaluation of various technologies in a cost-effective manner. Allowing the utilisation of cheap sensing technologies to explore integration problems and solutions when harmonising COTS technologies with DefStan 23-009 GVA.

Whilst relevant, the results within this chapter are only a compliment to the overall results of the entire thesis (presented within Chapter 8, Conclusion). The results provided here simply demonstrate that the proposed GSFEA can support the theories postulated within the beginning of this body of work.

The testbed utilises a selection of the use cases presented within this thesis and was used throughout the various chapters to provide an understanding of the following:

- An understanding of integration requirements for COTS technologies,
- A live demonstration to the UK MoD of the capabilities that can be gained from the integration of automotive COTS safety sub-systems within MCS,
- A diverse experimental testing environment for the architectures and frameworks presented within Chapters 4, 5 and 6.

7.2 Testbed Design

The sensor fusion architecture design has been implemented within a diverse complex testbed (please see Figure 7.1) to investigate further the requirements of COTS technologies end to end integration with a GVA compliant land platform. It was also used to further provide demonstration of military exploitation of different COTS sensing technologies.

Additionally, the testbed demonstrator was used to integrate the output of the GSFEA into the Intelligent Digital Assistant (IDA) (a separate work package and another students Ph.D. thesis) as loosely described in Figure 7.35, page 214 Enabling Autonomy.

The preliminary testbed platform/demonstrator (Figure 7.1 below) is used to demonstrate the integration and harmonisation of multiple COTS sensing technologies with current defence standards (e.g. DefStan 23-009 and DefStan 00-082). This is used to demonstrate use cases such as surround motion/object detection and remote vehicle recovery implementing the GSFEA described within Chapter 6, Generic Sensor Fusion Electronic Architecture.

The testbed provides the following use cases (all utilising current LOSA defence standards):

- Surround object detection (e.g. people / objects moving towards platform, range and position),
- Remotely operating X-by-Wire systems (e.g. operating wheel modules remotely and independently of each other with a HID in X-by-Wire mode),
- Remotely operating / viewing internal vision systems (e.g. accessing a DefStan 00-082 stream remotely whilst controlling the camera position with a HID in camera control mode),
- A GSIA providing the sensor interface to the Def Stan 23-009 environment.

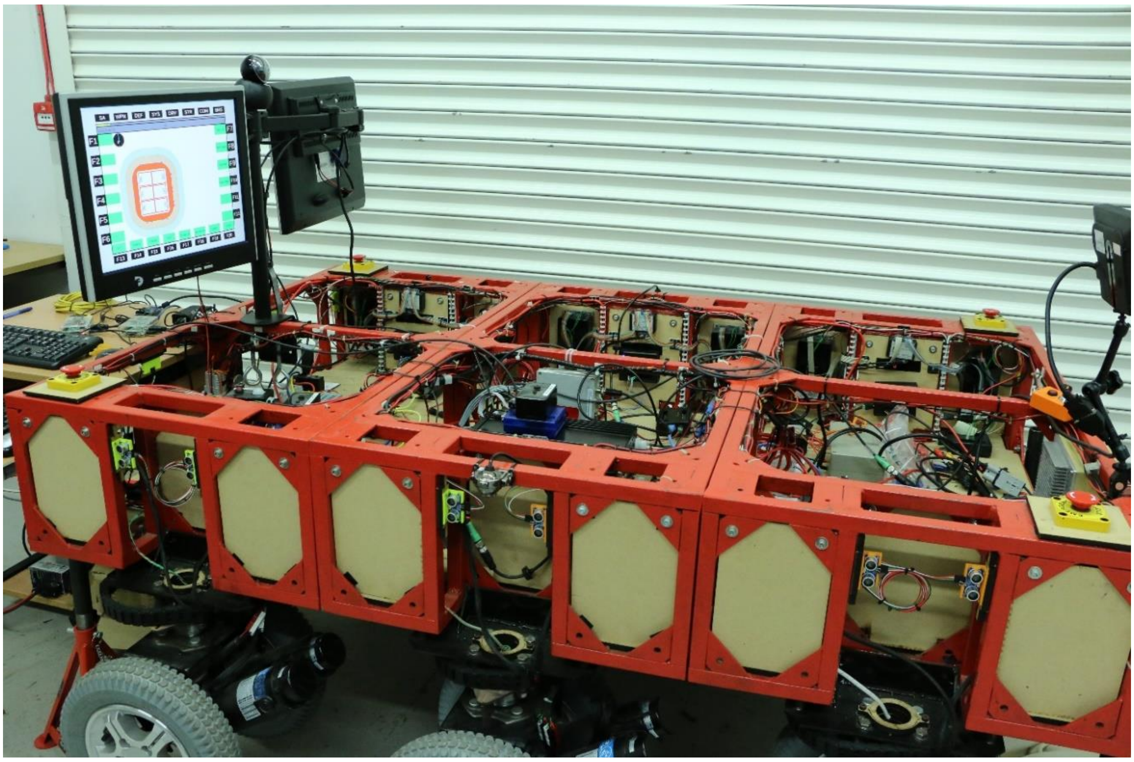


Figure 7.1 Def Stan 23-009 physical testbed / demonstrator platform

To support the aims discussed above, Figure 7.2, details the testbed demonstrator architecture being implemented within the platform shown above (Figure 7.1) and is based on the sensor fusion design presented within Chapter 6, Generic Sensor Fusion Electronic Architecture. This supports the fusion, integration and capabilities requirements and is the basis for the testbed demonstrator within a GVA environment. Figure 7.2 describes the multiple bus types supported, sensing technologies, GSFEA, system management and the motor controllers. As can be seen the entire testbed utilises a GVA compatible data model implementing DDS middleware as its data distribution solution.

7.2.1 Testbed Platform

Figure 7.2 Def Stan 23-009 physical testbed platform logical architecture

The testbed incorporates many hardware technologies from different manufacturers and many software technologies from different vendors (described within Table 7.1 below):

Table 7.1 Testbed Composition

Testbed Composition	
Component Group	**Description**
Hardware	• Intel based i386 micro motherboards (32bit), • BeagleBone Black (32bit embedded microcontroller) V2/3, • 1/10 Gigabit network switches, • Ultrasound range detection sensors (HC-SRF04), • Leddar tech range finding sensor, • Microsoft's Kinect V1, • Blade server cluster, • ASL 360 composite cameras (analogue), • Various HMI.
Software	• Real Time Innovations (RTI) Connext DDS middleware (V5.3.0), • Debian ARM (OS), • Debian 64, • SQLite3 (version 3.21.0), o SQLitebrowser (version 3.10.0), • QT (version 5.9.3), • Custom C, C++ code, • Custom assembly code, • IEEE 1588 Precision Time Protocol (node sync).
Network/communication	• Gigabit Ethernet, • Controller Area Network (CAN), • I2C bus, • Level driven bus, • Serial Peripheral Interface (SPI).

Figure 7.2 describes three replicated modules (Platform Module) PM1, PM2, PM3, designed to support modularity. Each module contains multiple sensor/sensor types, these sensors are connected to (software) fusion modules using a GVA adapter. This supports all communication protocols required by the sensors (e.g. SPI / I2C, CAN bus). The various modules communicate with each other utilising RTI DDS middleware coupled with the developed sensing and fusion data model. All of which is used as a platform to integrate sensing technologies.

Since the closure of the Vetronics Research Centre the wheeled platform testbed has been moved to a desktop variant as described below in Figure 7.3. Fortunately, this presented an opportunity to test and compare a best-case and worst-case network scenario. Where the UGV testbed would be the worst-case scenario running across the main Vetronics

Research Centre network with all other network traffic. The desktop testbed below would be representative of the best-case scenario (or normal use case) of a local network (such as that on a vehicle).

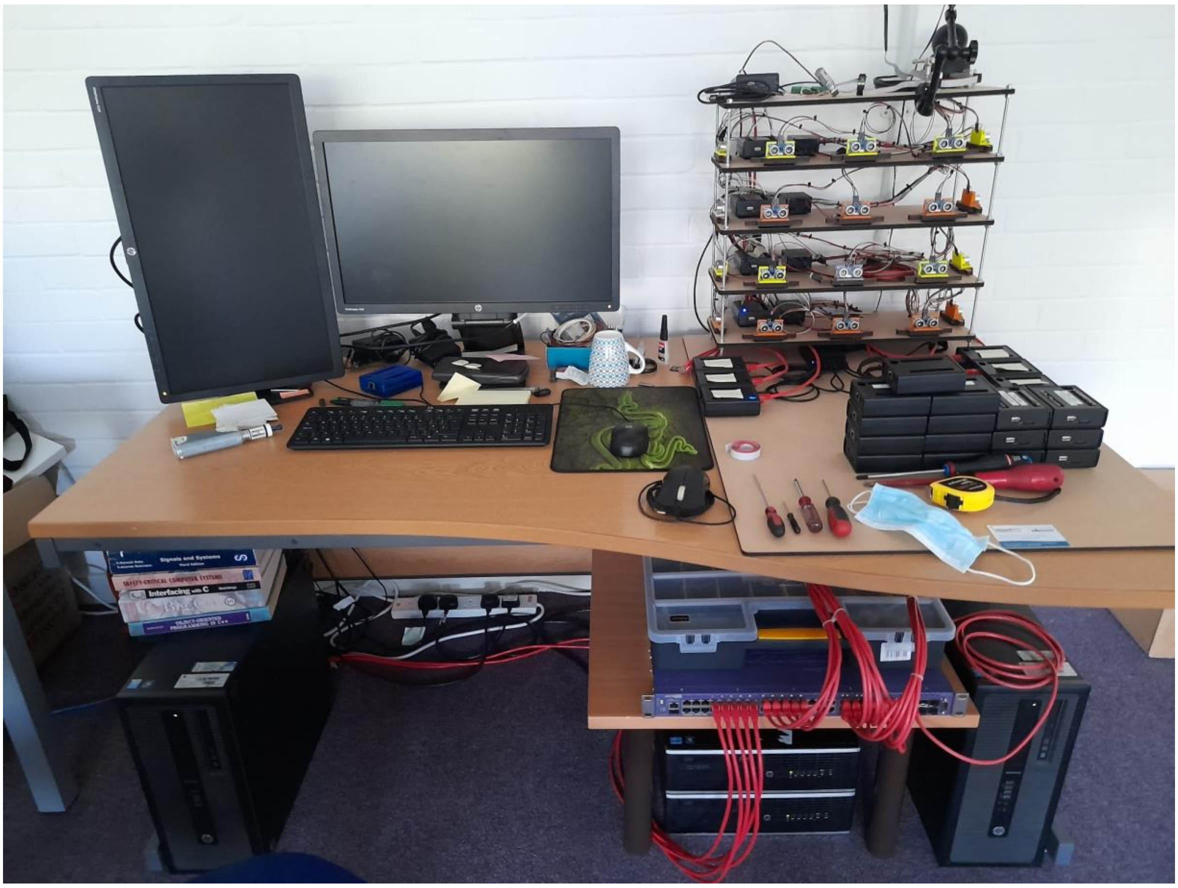


Figure 7.3 Desktop Testbed Variant

All of the same modules persist, the sensing modules can be seen on the desktop tower, the 6, motor controller BeagleBone blacks are included in front of the tower with the 3 PCs on the left of the image running SO_Pre_Pro, and CMM with the final machine being a backup file server (all the programs written for this research and results DB are contained and invoked and or modified from this machine).

7.3 Testing Methodology

A series of two experiment types were carried out with multiple components contained within each as described within Table 7.2.

Table 7.2 GSFEA Latency Experiment Structure

<table>
<tr><th>Latency Experiment Type</th><th>Rationale and description</th></tr>
<tr><td>Baseline testing
(Section 7.5)</td><td>Essentially this series of tests were conducted to collect a baseline latency metric.

These experiments capture the latency metric of DDS itself (running on the hardware described in this chapter), and the CAN bus (running on the BBBs). This then can be used to provide contrast to the measurements collected when the GSFEA is operating with IEEE 1588 PTP running (PTP is mandatory to retrieve accurate latency results for the GSFEA itself). Therefore, indicating the latency behaviour of the GSFEA proposed within this body of work.

The following data was collected:
CAN bus baseline,
RTI DDS perf test tool sending 1 MB/s.
RTI DDS perf test tool – best effort and reliable QoS, with and without IEEE 1588 PTP running. This was collected for each sensor types within the GSFEA data size in bytes (5 sets in total to represent the 5 sensor types).
The measurements collected above were collected and presented as described below:

Presented as a graph (for each data size in bytes):
Set A – reliable QoS with and without PTP,
Set B – best effort QoS with and without PTP,
Set C – Comparison of both QoS configurations with PTP.
These sets of measurements provide a point of reference for DDS data transmission alone, using the same size data as used in the GSFEA.</td></tr>
<tr><td>UGV and desktop testbeds
(Section 7.6)</td><td>Here latency measurements were collected for all sensor types with best QoS and IEEE 1588 PTP running on each node.

Which then provides an indication of the performance of the GSFEA when operating normally across both the UGV testbed and the desktop testbed.</td></tr>
<tr><td>Overall comparison of all of the above
(Section 7.7)</td><td>The data presented here is simply a set of graphs with all the data collected above collated, showing a comparative between RTI perf test tool (just DDS), the UGV testbed (worst-case scenario) and the desktop testbed (best-case scenario).</td></tr>
</table>

7.3.1 Testbed System Configuration and Composition

The system is comprised of the following programmes (described within Table 7.3) written in a mixture of C / C++ (mainly 2011) and assembly.

Table 7.3 Software developed for GSFEA testbed

Program and language	Description
SO_pre_processing (C/C++)	This program contains the main components of sensor processing. The software directly reflects the GSIA design and can operate in multiple modes (distributed, hybrid, centralised). Mode select is provided through the use of simple Boolean flags.
SO-GPS-gen-Mcpp (C++)	Provides the structures for GPS data to be transmitted using DDS.
SO-Leddar-gen-Mcpp (C++)	Provides the structures for CAN Leddar sensor data to be transmitted using DDS.
SO-lidar-gen-Mcpp (C++)	Provides the structures for Lidar data to be transmitted using DDS.
SO-radar-gen-Mcpp (C++)	Provides the structures for Radar data to be transmitted using DDS.
SO-SRF-gen-Mcpp (C++)	Invokes hcsr04.bin (assembly file when ran reads sonic range finding sensors and places results in memory to be collected by the C compilation unit within SO-SRF-gen-Mcpp). Also provides the data structures for data transmission within DDS, once sensor data retrieved from the assembly program.
Capability-Management-Module-Mcpp (C++)	Reflects the Capability Management Module (CMM) of the GSFEA.
CMM-simple-sub-Mcpp (C++)	Reflects the final stage of the GSFEA, this would be where the HMI is provided the fused data.
GetClocksSharedLib (C++)	Shared library written to support the retrieval of multiple hardware clocks within the CPU.
GetClocksStaticLib (C++)	Static library written to support the retrieval of multiple hardware clocks within the CPU.

The latency results were captured within the main program SO_Pre_Pro by creating a class on separate threads for DB access. SQLite was chosen to manage the system database due to being lightweight, simple and having reasonably fast access times [118]. Below is a basic description of how results such as latency were captured.

SO_Pre_Pro contains 5 total DDS listeners named as:

- so_gps_listener,
- so_lidar_listener,
- so_srf_listener,
- so_radar_listener,
- so_Leddar_listener.

DDS listeners provide the least latency end to end compared to DDS wait sets, which is why listeners were originally selected. However, the drawback is that each listener runs on the main thread, therefore once triggered until you exit the call to read, no other listeners can trigger. Generally, this is fine unless you're dealing with significant data sizes (such as running multiple Lidar samples along with all other sensing samples). To handle this, methods were created to provide SO_Pre_Pro with the ability to destroy listeners and spawn another instance of SO_Pre_Pro passing flags to identify which listeners to create. This would generally be the culprit listener which was overloading the system (i.e. Lidar data). This was achieved by creating generic objects for the publishers, subscribers, readers and writers. With the use of Boolean type flags, the architecture can control which subscribers / publishers (and therefore listeners) to create or destroy at run time. Thus, allowing not only a generic approach but also a measure of flow control and resilience and mode switching (from centralised to hybrid / distributed, mode 1 or mode 2 as described in Chapter 6). A snippet can be seen within 10.4 Appendix D: Selection of C++ code snippets, detailing how this is achieved.

As discussed in previous chapters IEEE 1588 Precision Time Protocol (PTP) [115] was used to synchronise all the hardware clocks within the system (all the BeagleBone Blacks and the PC's NICs required a hardware timestamp to prevent significant drift and loss of precision).

The time the data is sent is recorded immediately upon entry to the class that is about to write the data to the wire. The sensor data is then transmitted, and the time of generation is contained within the data payload. Once the listener fires on the subscriber end the time is again immediately collected and stored. The time the message was generated is subtracted from the time the message was received (hence providing the latency) and written to the DB along with other sensor information (sensor data itself, sensor name / ID etc.).

Each DDS listener class has access to 2 Cpp vectors (shown below, taken from so_Leddar_listener.h):

```
// vectors used for database mutexed insert
std::vector<SUB_TYPE_1>* so_Leddar_data_vector__mutex_A = new std::vector<SUB_TYPE_1>;
std::vector<SUB_TYPE_1>* so_Leddar_data_vector__mutex_B = new std::vector<SUB_TYPE_1>;

// filling the vectors based on mutex
if(mutex_A_locked == false) {

//if(use_ncurses == false) {std::cout << "fired listener db mutex A" << std::endl;}

    so_Leddar_data_vector__mutex_A->push_back(so_Leddar_data_seq.get_at(i));

  }else if (mutex_B_locked == false) {

//if(use_ncurses == false) {std::cout << "fired listener db mutex B" << std::endl;}

    so_Leddar_data_vector__mutex_B->push_back(so_Leddar_data_seq.get_at(i));
}
```

These vectors operate on a mutex paradigm. That is, they are locked and unlocked within the so_db_access.ccp class. Essentially the contents of the currently locked vectors from each listener are written to the DB and then the locks are flipped before the class returns (a pause is provided to allow for asynchronous nature of the various sensors data rates). Thus, allowing the other vector to be written to whilst the previous one is now being written to the DB and so on.

All the following measurements were captured using the MONOTONIC_RAW clock, this is to allow the use of PTP to slew the oscillator as needed to synchronise all system nodes.

7.4 Testbed performance metrics

The following measurement sets have been designed to simply provide examples of the architecture functioning with all the models designed and described within this body of work (shown in Figure 6.16 GSFEA systems view, page 162 with the accompanying .idl files shown within 10.2 Appendix B: GSFEA Data Model .IDL, page 238).

Throughput has not been considered within the measurements collected in the following sections. Whilst throughput is applicable for system design (especially when considering LiDAR data size) it is not considered critical. However, latency is considered important within the context of safety as part of the military use cases, therefore, latency is all that is measured.

All tests are run with all sensor nodes waiting to publish (that is they are all started and waiting to begin publishing as soon as a subscriber joins the DDS domain). Once all are running SO_Pre_Pro is invoked, and all subscribers are started. DDS listeners were selected as the trigger for message collection from subscribers, as they offer the least latency. Default QoS profiles are used as this was considered tailoring, these measurements are intended to provide an overall view of DDS and the GSFEA operating together in a default mode.

7.5 Baseline testing

The following were a series of tests completed to provide a baseline or reference point for the GSFEA measurements collected and presented within this chapter. This is to achieve a view of the latency impact of the architecture design (which includes the use of DDS).

The purpose is to understand the impact of Best Effort QoS versus Reliable QoS and the impact of DDS running with and without IEEE 1588 PTP on the same network and device. Therefore, we can later assess the overall impact of the GSFEA design.

7.5.1 CAN frame latency

Below is a simple example of 100 (Figure 7.4) and 1000 (Figure 7.5 and Figure 7.6) CAN frames being sent over the CAN bus. This is a measurement of the frame being transmitted to when it was received by the node. This is only relative to the Leddar sensor attached to the CAN controller within the BeagleBone Black (BBB) (the transceiver needed to be added separately on the bus).

These measurements were captured using a standard industry tool provided by Vector CANoe [119]. Interestingly, we can see what appears to be some form of uniform, repeating jitter within the CAN bus (indicated by the red circle within Figure 7.4). It is not entirely clear what is causing this within the CAN bus. It is possible that it is related to the Vector CANoe tool itself as described within this knowledge base article found here [120]. Another reason could be related to the Leddar sensor CAN controller and frame processing itself.

This jitter has no impact on the results presented within this chapter as it is used as a baseline for reference, to all other measurements taken when sending data received from the CAN bus over the DDS segments. We can simply take this into account when measuring the Leddar sensor to CAN to DDS interface measurements.

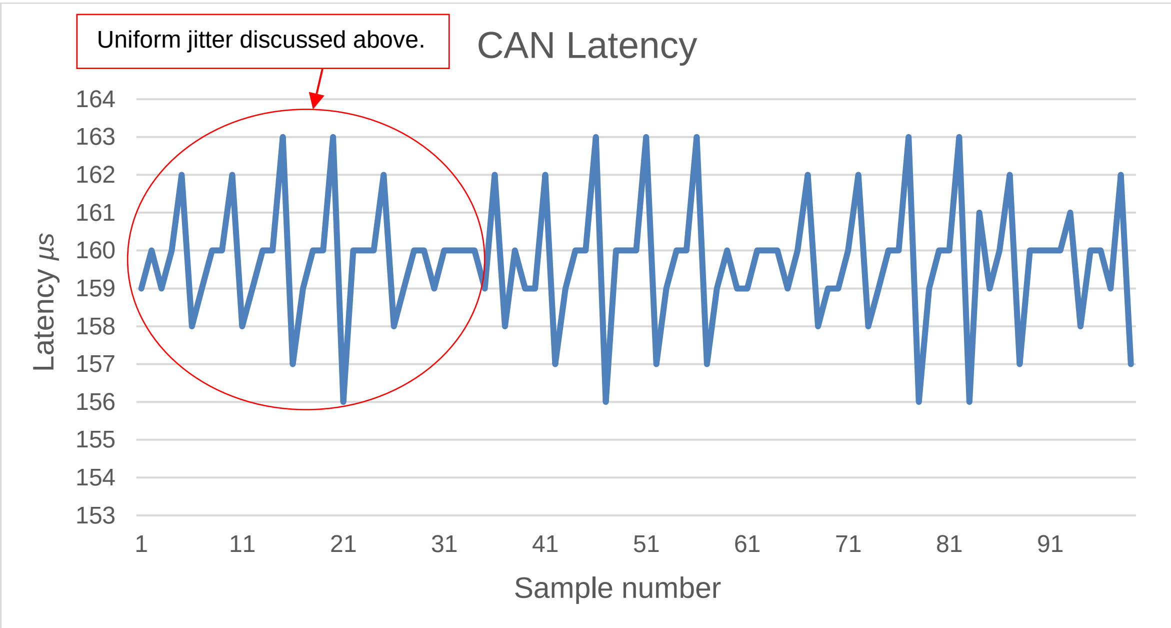


Figure 7.4 CAN frame latency test

Figure 7.5 and Figure 7.6 show the CAN latency captured again with CANoe [119]. Measurements were taken over 1000 CAN frames. These measurements were captured using the MONOTONIC_RAW clock. As shown the average latency is a steady 160 μs with small standard deviation of 2.5 μs.

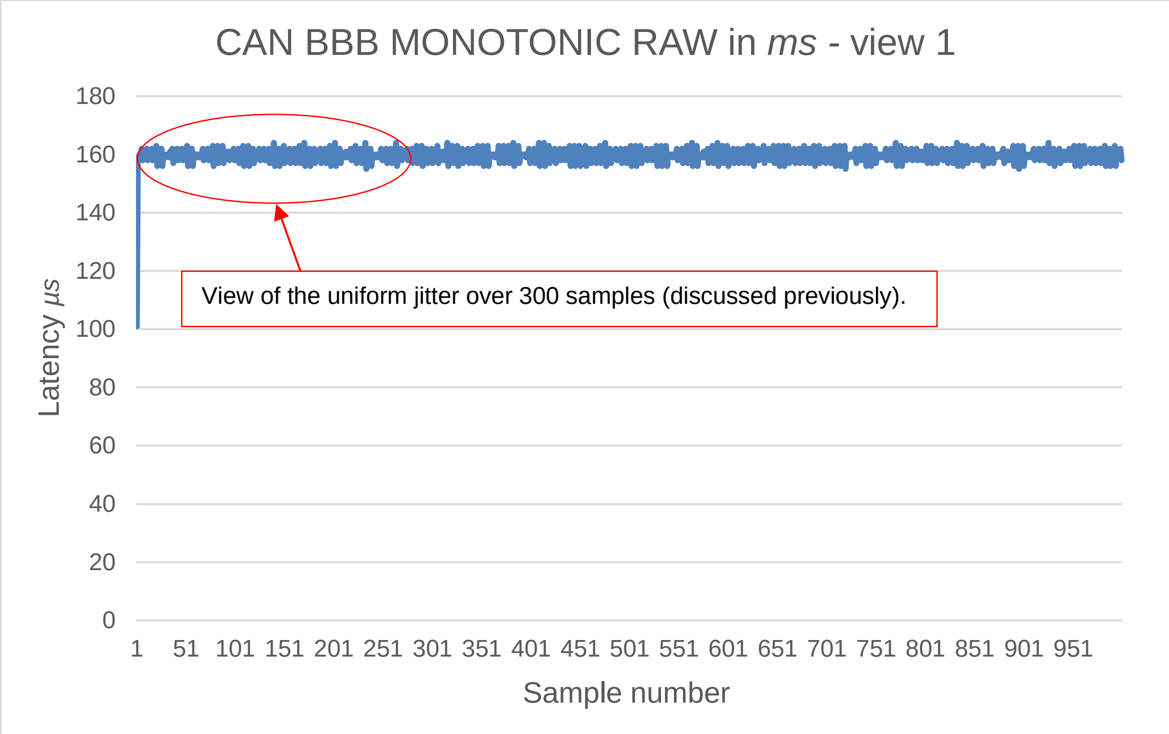


Figure 7.5 CAN BBB MONOTONIC RAW in *us* – view 1

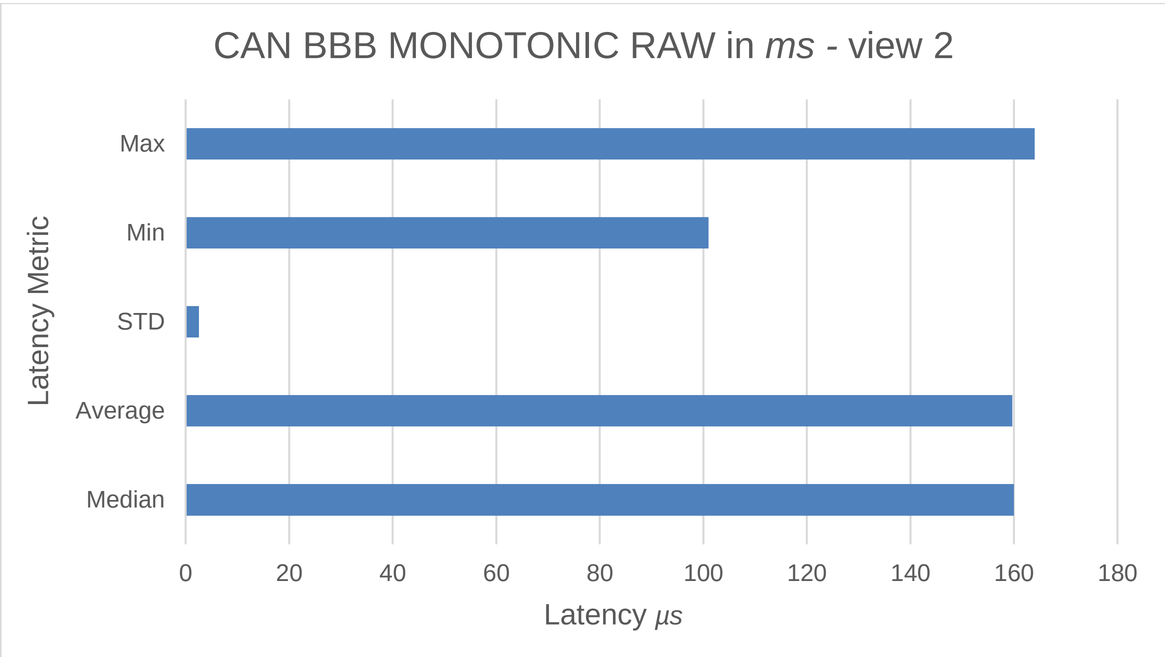


Figure 7.6 CAN BBB MONOTONIC RAW in *us* – view 2

As we can see from Figure 7.4, Figure 7.5, Figure 7.6 the latency is a steady average of 160 *μs.* Providing a reference point for the Leddar sensor when being utilised over DDS allowing the deduction of the impact of DDS and the GSFEA components over the base CAN bus latency.

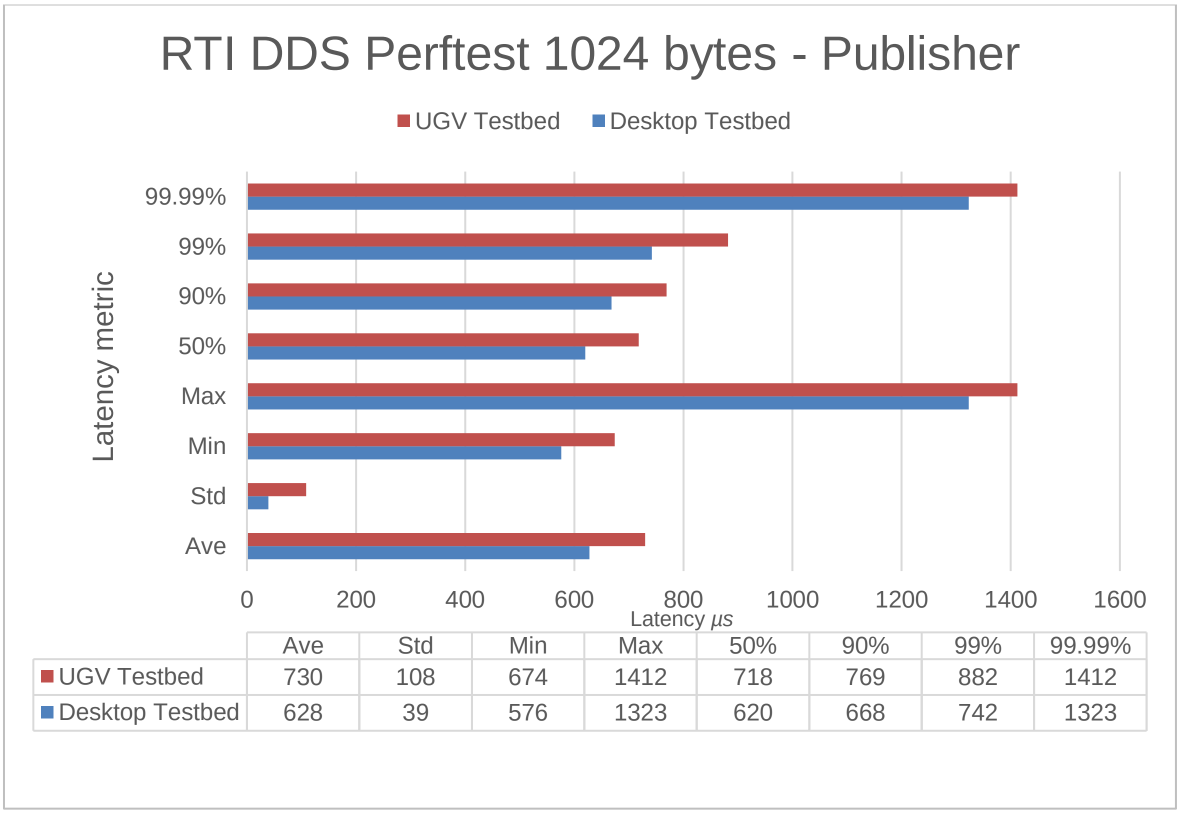
7.5.2 RTI DDS performance testing (RTI Perf Test Tool)

Extensive measurements were taken utilising RTIs performance tool, RTI Perf test 2.4.0 [121]. The reason for doing so was to verify the basic performance of DDS alone, so as to compare to the measurements taken within the testbed latency tests. The following tests were run across the main network using standard 1Gb Ethernet network, using the hardware described previously within this chapter.

7.5.3 RTI Perf Test, 10000 samples, 1024 bytes per sample

Figure 7.7 is simply a performance test with 1MB to assess the baseline network latency of the DDS installation running on the hardware that comprised the UGV / desktop testbed.

Within Figure 7.7, we can see very small latency results for sending 10000 samples of 1MB at 50 samples a second. The latency was on average 679 μs between the UGV and desktop testbeds. Thus, providing a reference to basic DDS performance of both testbeds.

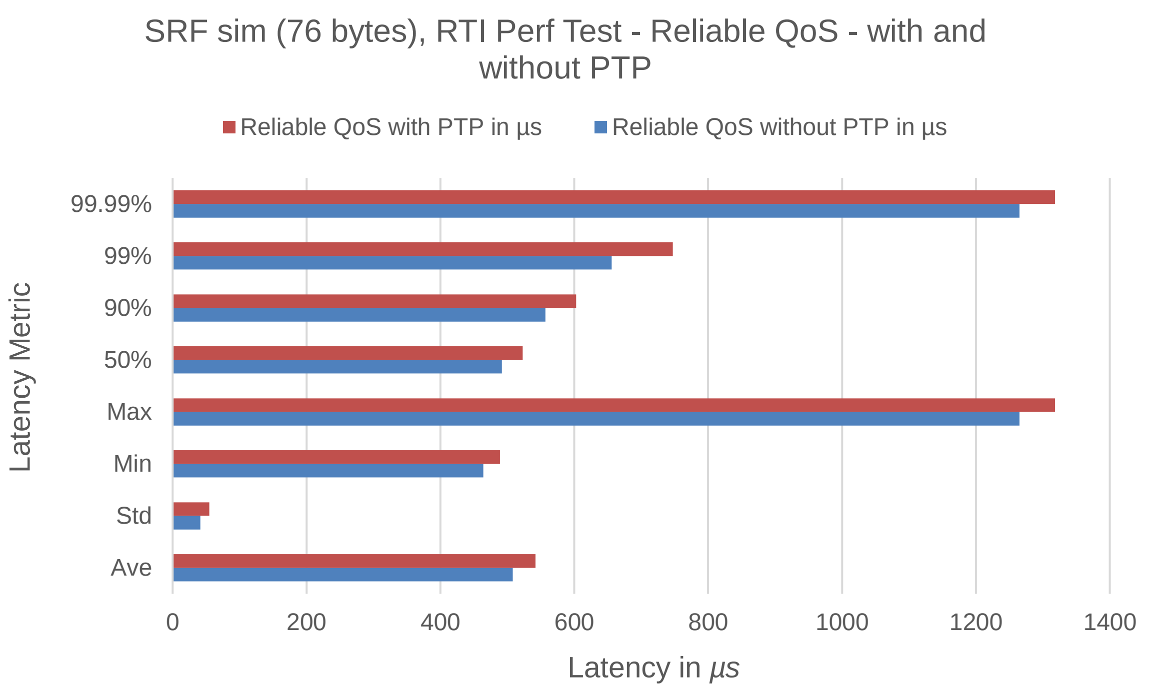


	Ave	Std	Min	Max	50%	90%	99%	99.99%
UGV Testbed	730	108	674	1412	718	769	882	1412
Desktop Testbed	628	39	576	1323	620	668	742	1323

Figure 7.7 RTI DDS Perftest 1024 bytes, 10,000 samples – Publisher

7.5.4 RTI Perf Test - SO_SRF data length 76 bytes on the wire

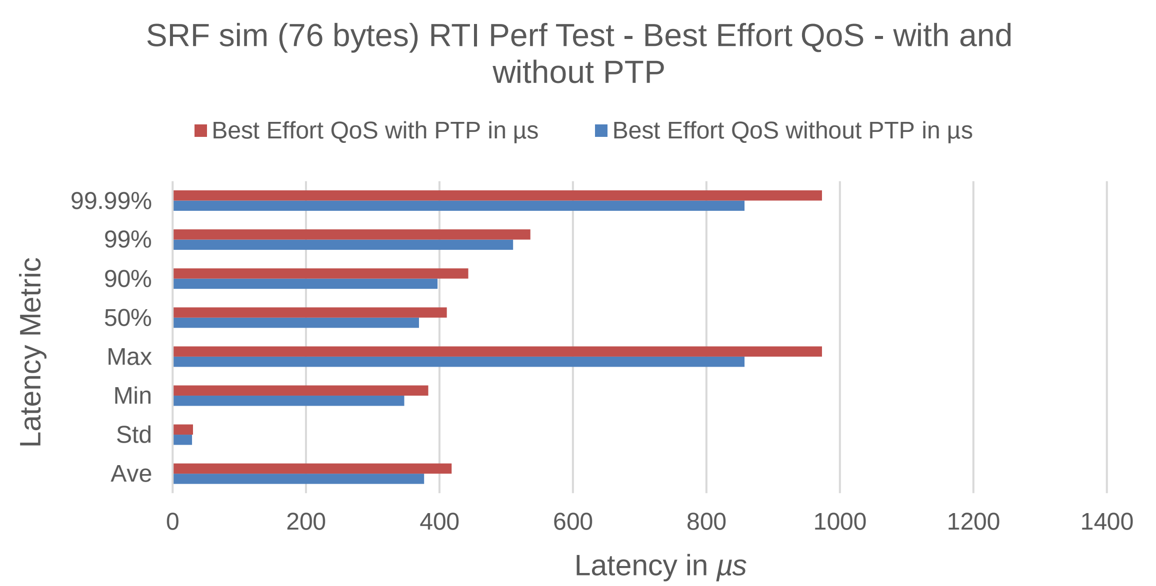
Figure 7.8 shows the impact of reliable QoS with and without PTP on the wire, there is an average latency delta of 34 μs between the two measurements.



	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Reliable QoS with PTP in µs	542	55	489	1318	523	603	747	1318	6.37
Reliable QoS without PTP in µs	508	41.3	464	1265	492	557	656	1265	5.98

Figure 7.8 SRF data sim RTI Perf Test - reliable QoS with and without PTP running, (set A)

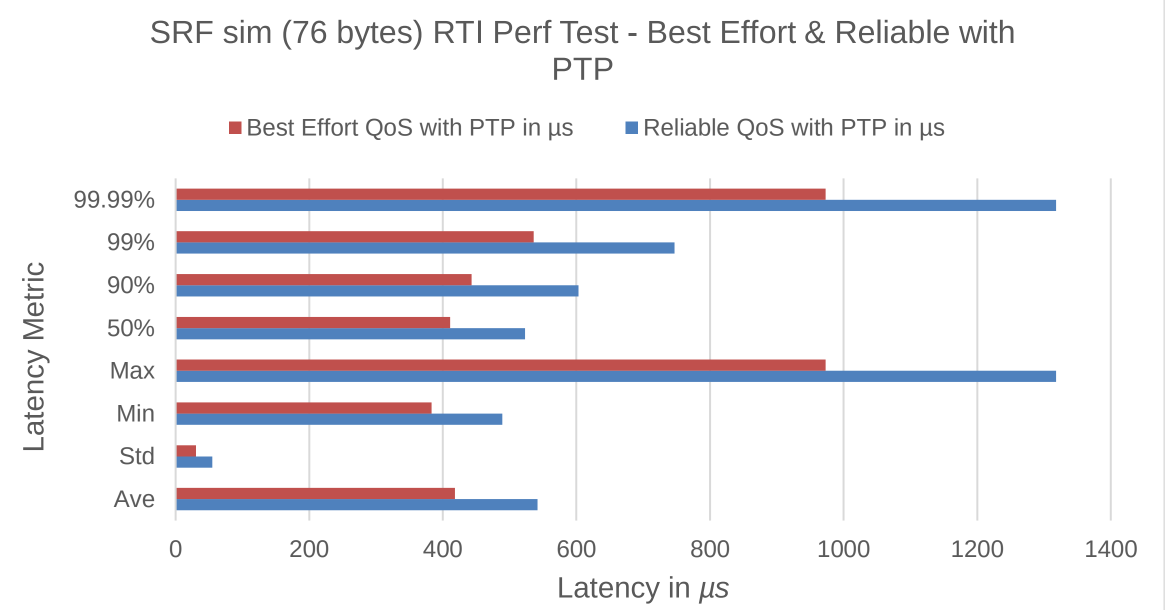
Figure 7.9 shows an average latency delta of 41 μs between the 2 measurements when using best effort QoS. PTP added on average 37.5 μs with a 34 μs delta between reliable QoS with and without PTP and 41 μs delta for best effort QoS.



	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	418	30.4	383	973	411	443	536	973	3.1
Best Effort QoS without PTP in µs	377	29.3	347	857	369	397	510	857	2.76

Figure 7.9 SRF data sim RTI Perf Test - best effort QoS with and without PTP running, (set B)

Finally, Figure 7.10, shows the latency average delta between the 2 QoS configurations (with PTP running), being 124 *µs.* If we subtract the highest average latency delta from Set B, we can see an average latency of 83 *µs*.

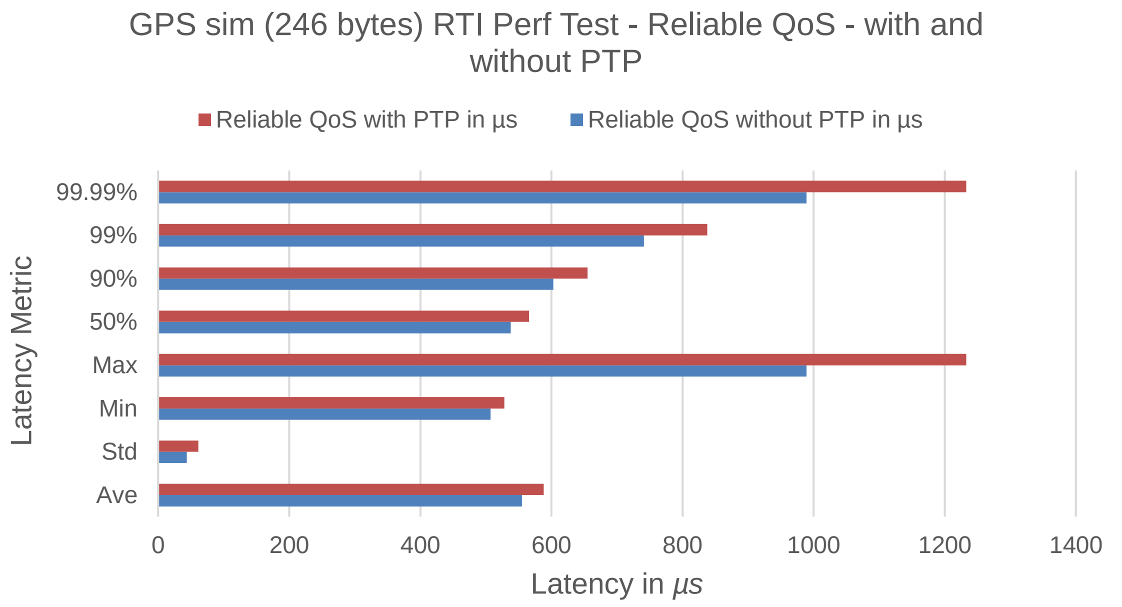


	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	418	30.4	383	973	411	443	536	973	3.1
Reliable QoS with PTP in µs	542	55	489	1318	523	603	747	1318	6.37

Figure 7.10 SRF data sim RTI Perf Test, best effort and reliable QoS with PTP running, (set C)

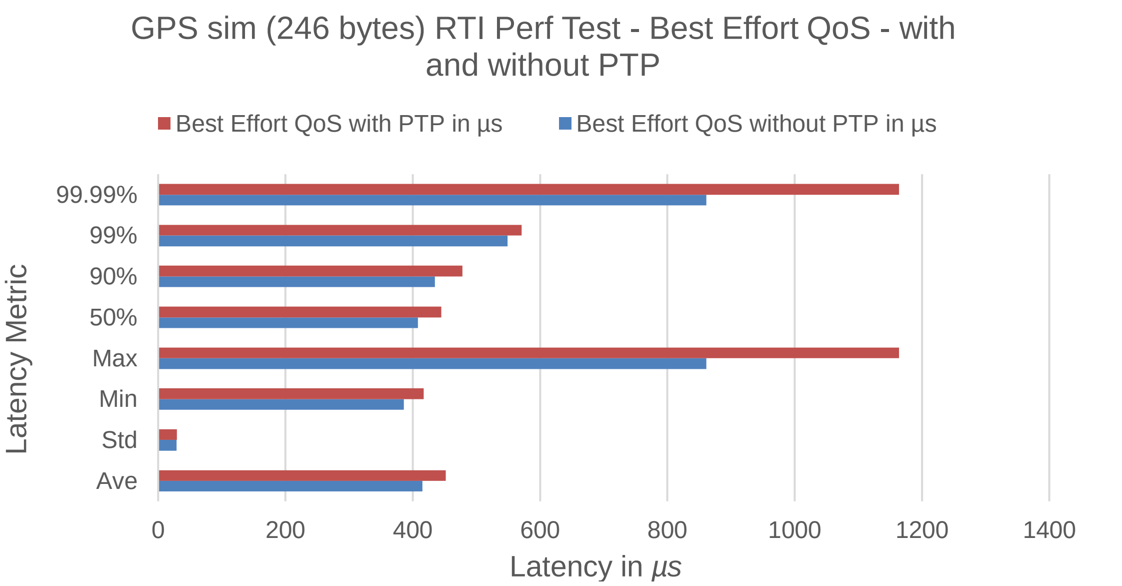
7.5.5 RTI Perf Test - SO_GPS data length 246 bytes on the wire

Figure 7.11 and Figure 7.12 show very similar results with the average delta between running PTP and not running PTP with both QoS configurations (reliable and best effort) to be 35 μs.



	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Reliable QoS with PTP in µs	588	61.2	528	1233	566	655	838	1233	6.44
Reliable QoS without PTP in µs	555	43.9	507	989	538	603	741	989	6.19

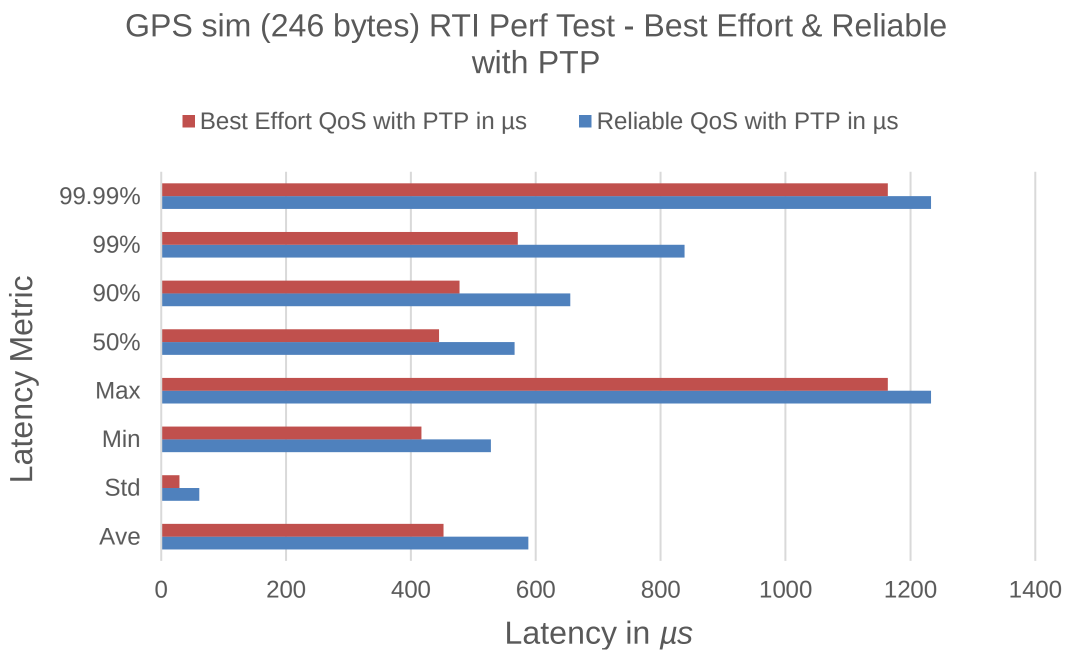
Figure 7.11 GPS data sim RTI Perf Test - reliable QoS, with and without PTP running, (set A)



	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	452	29.4	417	1164	445	478	571	1164	3.07
Best Effort QoS without PTP in µs	415	29	386	861	408	435	549	861	2.8

Figure 7.12 GPS data size RTI Perf Test - Best Effort QoS - with and without PTP running, (set B)

Figure 7.13 shows the delta between reliable and best effort QoS being 136 μs minus the average latency delta of PTP (35 μs) is 101 μs.

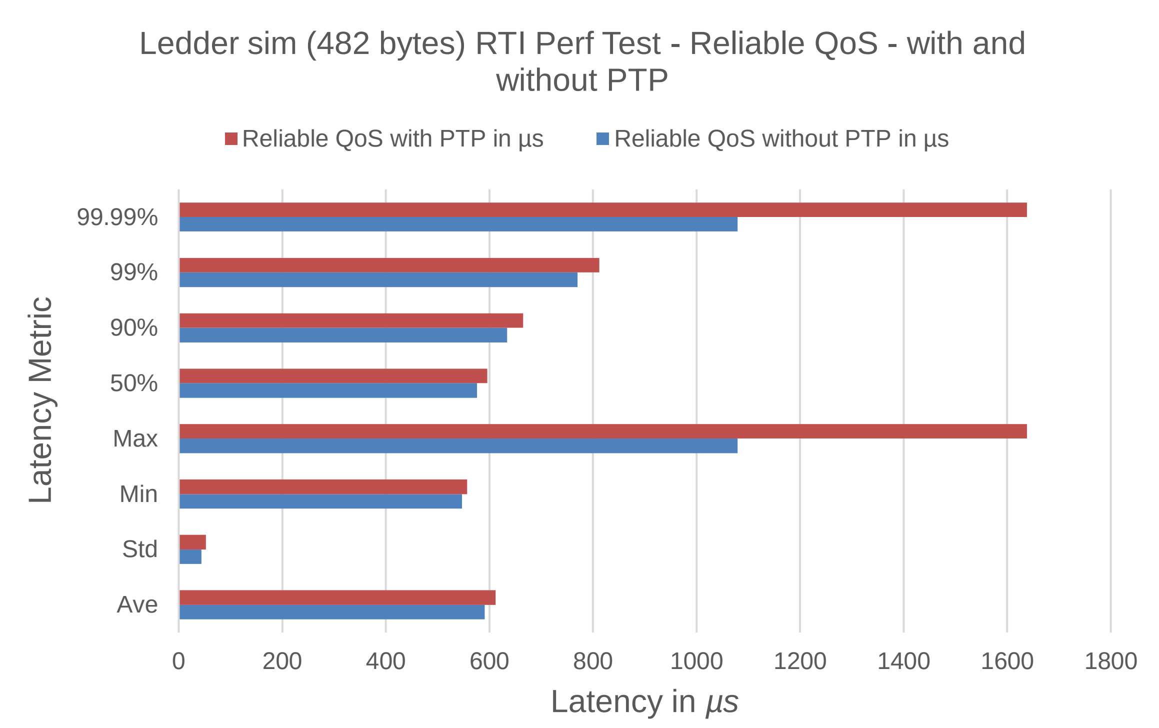


	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	452	29.4	417	1164	445	478	571	1164	3.07
Reliable QoS with PTP in µs	588	61.2	528	1233	566	655	838	1233	6.44

Figure 7.13 GPS data size RTI Perf Test - Best Effort & Reliable with PTP running, (set C)

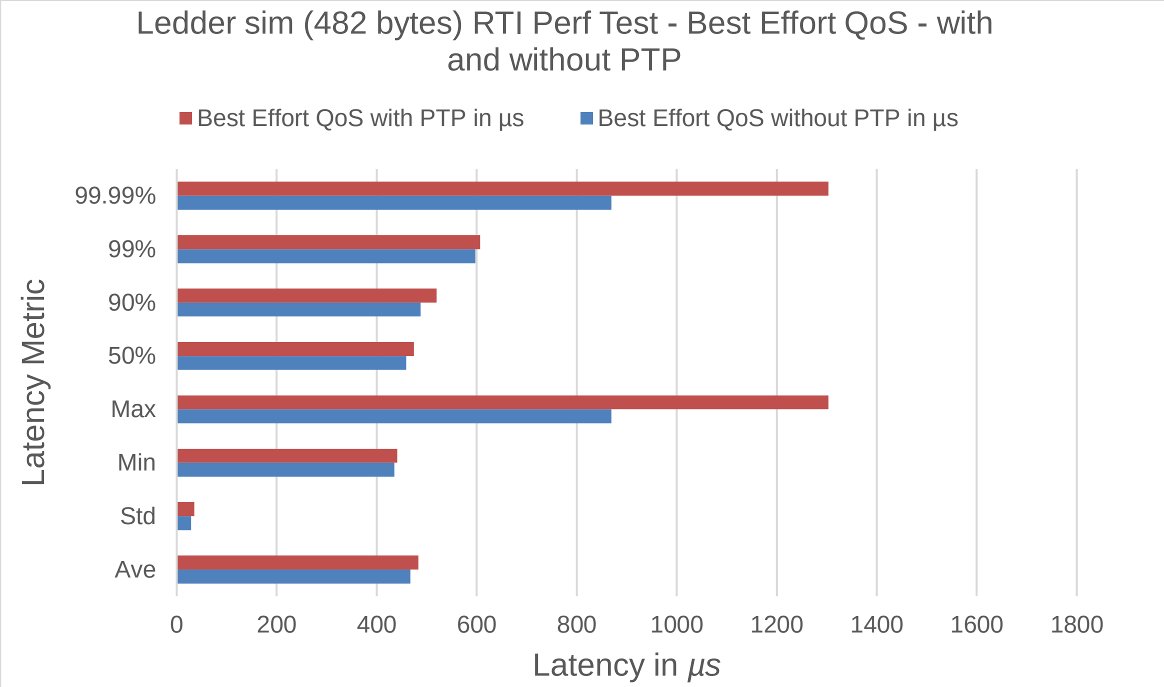
7.5.6 RTI Perf Test - SO_Leddar data length 482 bytes on the wire

Figure 7.14, Figure 7.15 and Figure 7.16 show very similar results to the above testing for the Leddar sensor data size on the wire. The delta between best effort and reliable QoS again is a base average latency of 129 *µs* minus the average latency delta of running PTP being only 5 *µs,* giving an overall average latency between the 2 QoS configurations of 124 *µs*. With PTP again on average having practically no impact on the message latency.



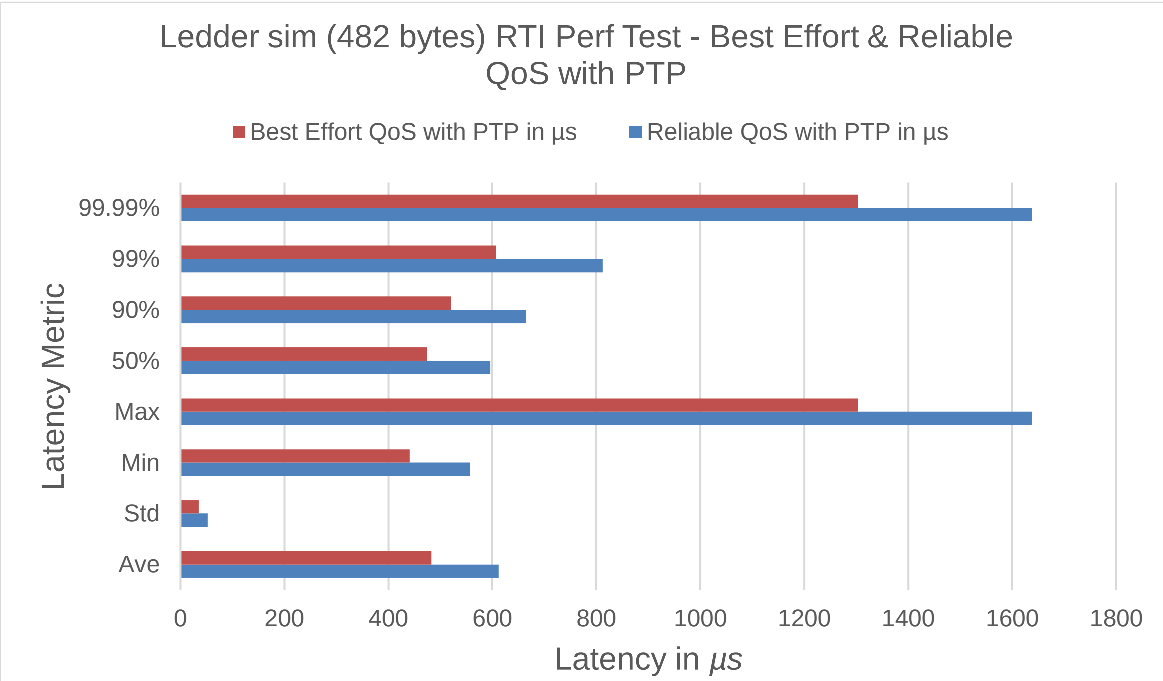
	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Reliable QoS with PTP in µs	612	52.6	557	1638	596	665	812	1638	6.15
Reliable QoS without PTP in µs	591	43.7	547	1079	576	634	770	1079	6.06

Figure 7.14 Leddar data size RTI Perf Test - Reliable QoS - with and without PTP running, (set A)



	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	483	35.2	441	1303	474	520	607	1303	2.98
Best Effort QoS without PTP in µs	467	28.5	435	869	459	488	597	869	2.91

Figure 7.15 Leddar sim RTI Perf Test - Best Effort QoS - with and without PTP running, (set B)

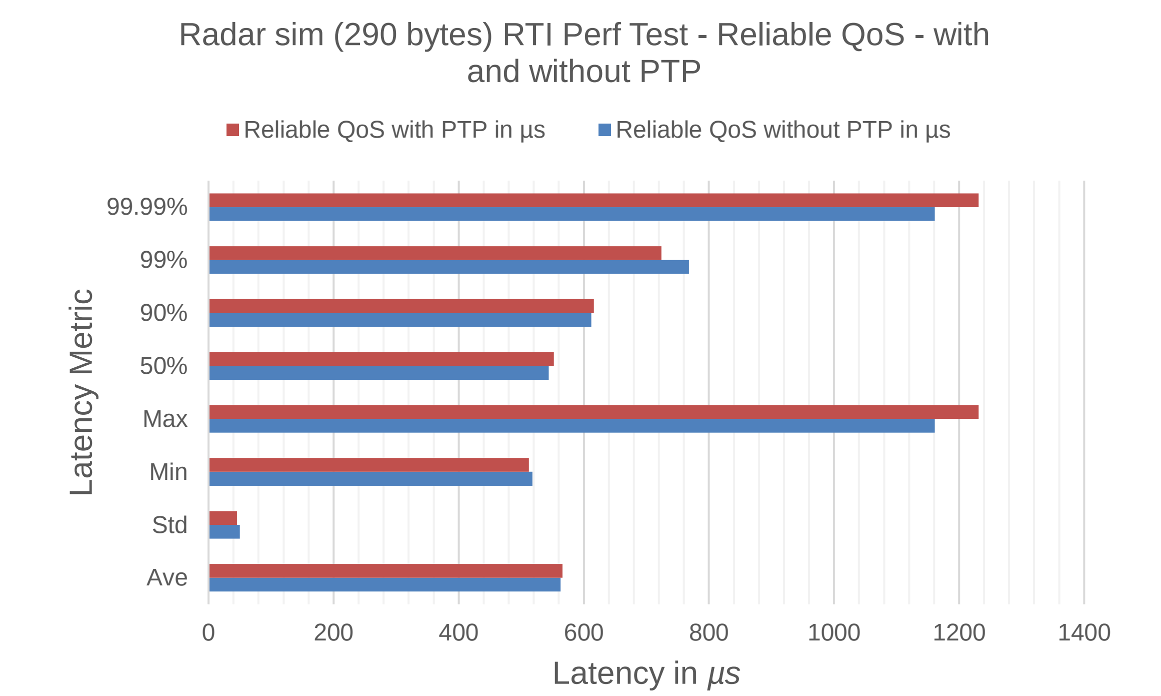


	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	483	35.2	441	1303	474	520	607	1303	2.98
Reliable QoS with PTP in µs	612	52.6	557	1638	596	665	812	1638	6.15

Figure 7.16 Leddar sim RTI Perf Test - Best Effort & Reliable with PTP, (set C)

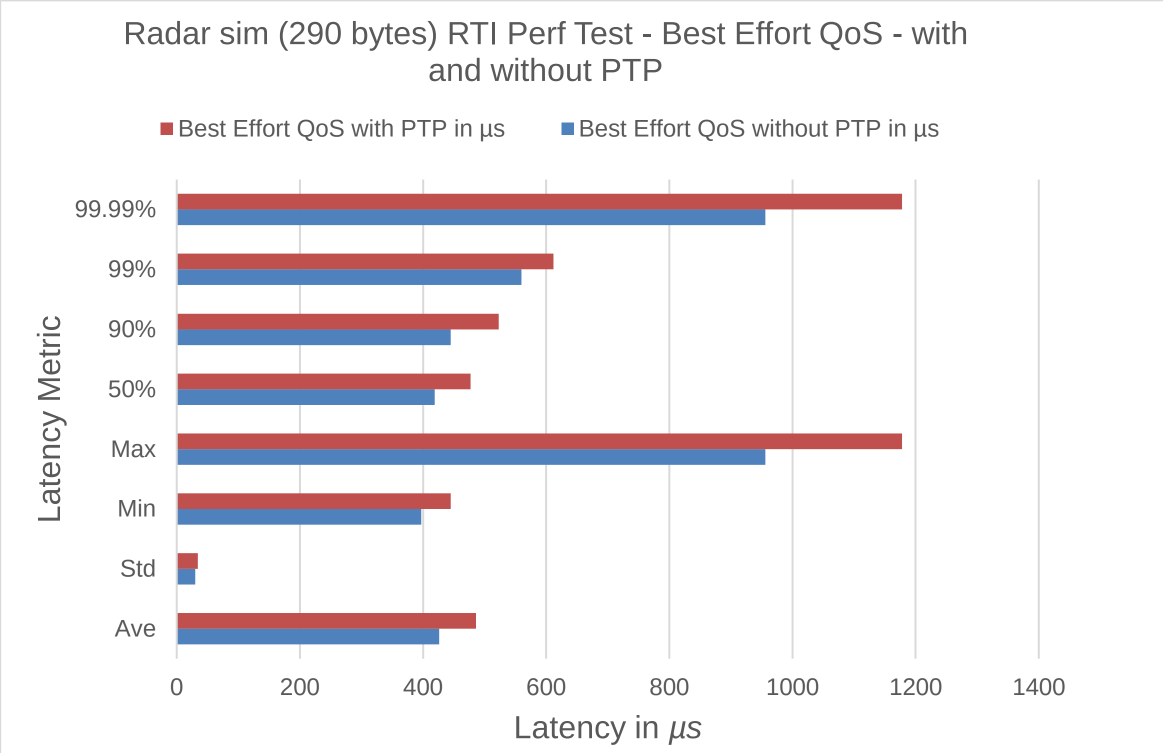
7.5.7 RTI Perf Test - SO_Radar data length 290 bytes on the wire

Figure 7.17, Figure 7.18, Figure 7.19 again show very similar results as the measurements taken above (section 7.5.6) and bear no significant differences.



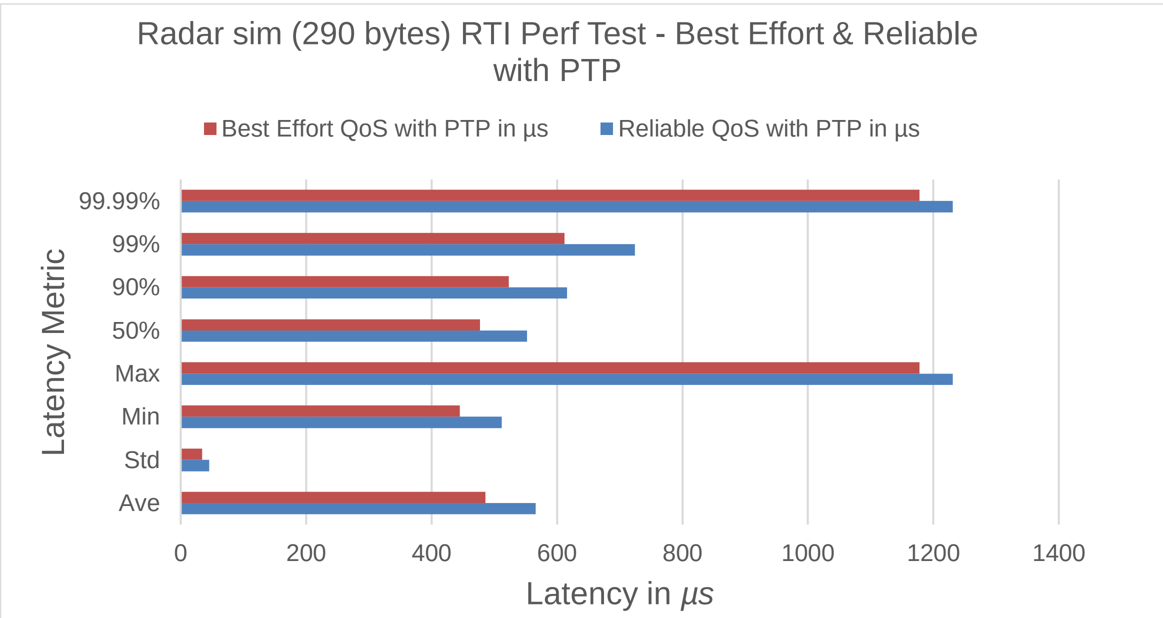
	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Reliable QoS with PTP in µs	566	45.6	512	1231	552	616	724	1231	6.05
Reliable QoS without PTP in µs	563	50.3	518	1161	544	612	768	1161	6.08

Figure 7.17 Radar data size RTI Perf Test - Reliable QoS - with and without PTP running, (set A)



	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	486	34.3	445	1178	477	523	612	1178	3.02
Best Effort QoS without PTP in µs	426	30	397	956	419	445	560	956	2.85

Figure 7.18 Radar data size RTI Perf Test - Best Effort QoS - with and without PTP running, (set B)

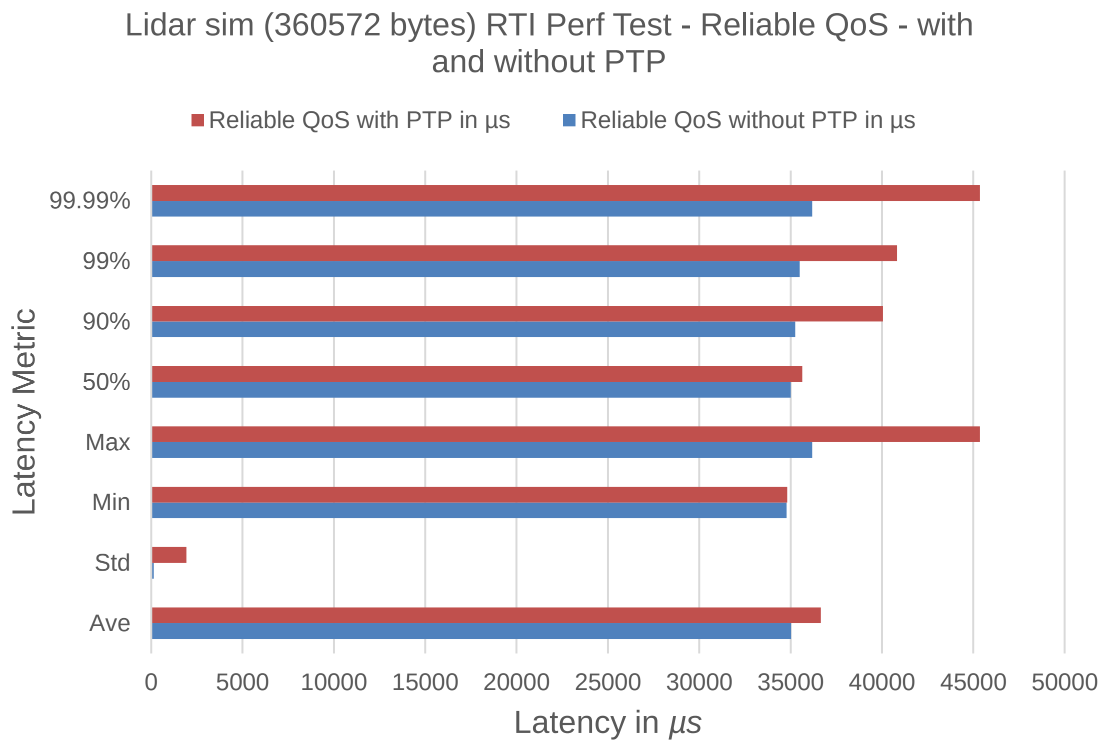


	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	486	34.3	445	1178	477	523	612	1178	3.02
Reliable QoS with PTP in µs	566	45.6	512	1231	552	616	724	1231	6.05

Figure 7.19 Radar data size RTI Perf Test - Best Effort & Reliable with PTP running, (set C)

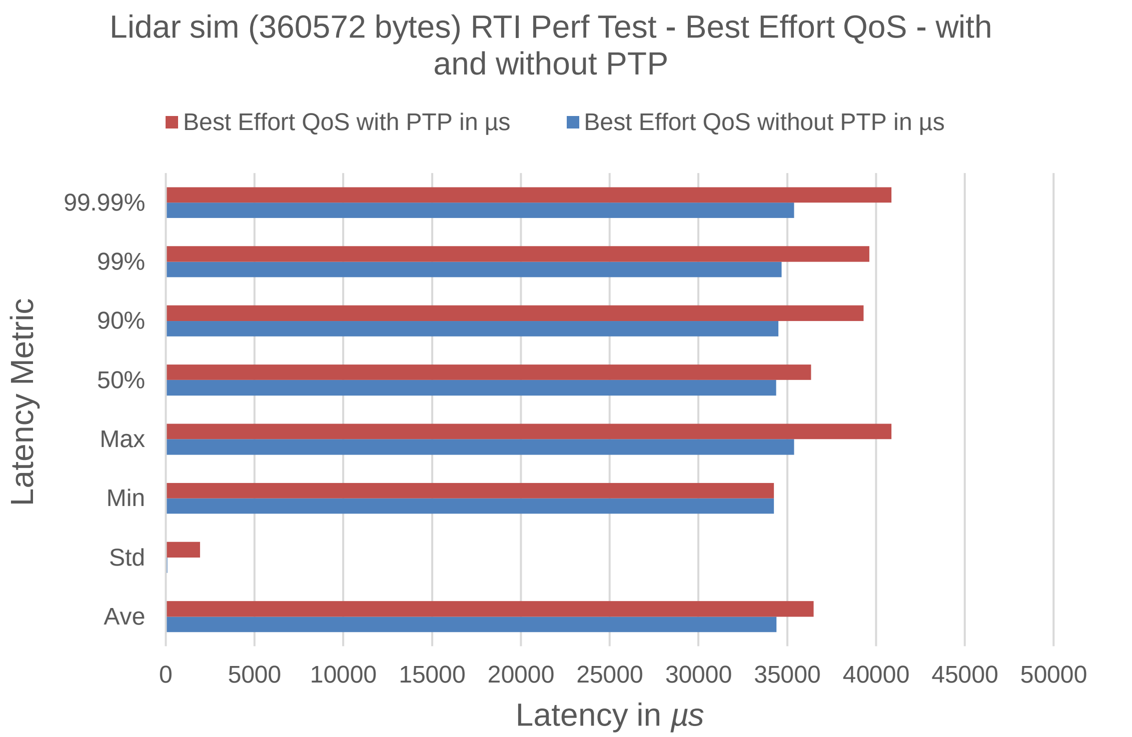
7.5.8 RTI Perf Test - SO_Lidar data length 360572 bytes on the wire

Figure 7.20, Figure 7.21, Figure 7.22 provides the results of the largest data set within the testing environment, the Lidar sensor. We can see around a 5.5% increase in latency when running reliable QoS with PTP versus no PTP. However, best effort produces a slightly larger result of 5.7% (with a delta of 2088 μs) between running PTP and not running PTP. The reason for the increase is unknown, the overall latency differences between using reliable versus best effort are as expected, with reliable being on average 200 μs more than best effort.



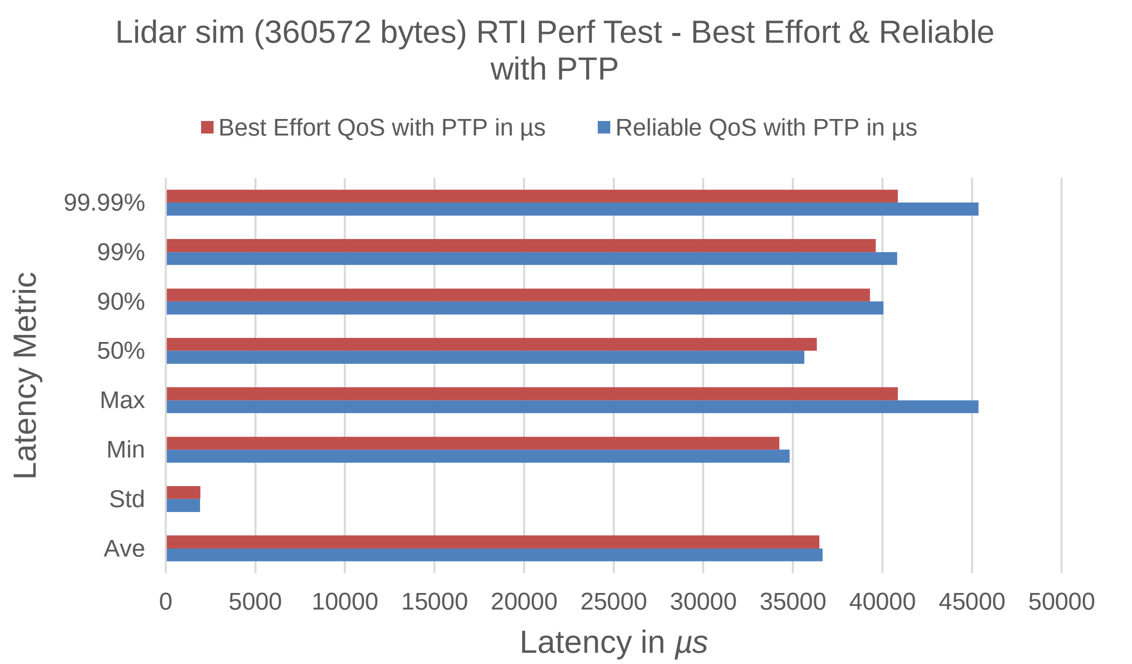
	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Reliable QoS with PTP in µs	36660	1919.6	34818	45363	35647	40058	40825	45363	19.74
Reliable QoS without PTP in µs	35032	144.7	34778	36177	35002	35247	35495	36177	19.98

Figure 7.20 Lidar data size RTI Perf Test - Reliable QoS - with and without PTP running, (set A)



	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	36480	1926.6	34253	40865	36336	39298	39626	40865	14.36
Best Effort QoS without PTP in µs	34392	84.5	34250	35394	34384	34498	34681	35394	14.93

Figure 7.21 Lidar data size RTI Perf Test - Best Effort QoS - with and without PTP running, (set B)



	Ave	Std	Min	Max	50%	90%	99%	99.99%	CPU %
Best Effort QoS with PTP in µs	36480	1926.6	34253	40865	36336	39298	39626	40865	14.36
Reliable QoS with PTP in µs	36660	1919.6	34818	45363	35647	40058	40825	45363	19.74

Figure 7.22 Lidar data size RTI Perf Test - Best Effort & Reliable with PTP running, (set C)

7.5.9 Summary Baseline Testing

These measurements were selected to give an overall baseline of the DDS transport mechanism with samples reflecting the size of all the sensing technologies used within the testbed demonstrator. The data sizes were calculated using wire shark with the real sensors with the publisher running on a single BeagleBone Black and the subscriber running on another BeagleBone Black connected to the same switch.

For each sensor type 3 sets of measurements were taken across 10000 samples sent:

- **Set A** – examines reliable QoS with and without PTP to assess the impact of running PTP.
- **Set B –** examines best effort QoS with and without PTP to assess the impact of running PTP and also provides a cross reference with the above set to quantify and corroborate the impact of selecting best effort or reliable.
- **Set C –** measures best effort and reliable with PTP to support and cross reference with set A, and set B for validity.

Interestingly, what we can see from the testing section is the warmup period for DDS where domain participant discovery takes place. This can be seen in all of the results with the deltas between the minimum latency results and 99.99 percentile latency measurements. This period when the discovery phase takes place for all nodes can be approximately a 40% increase in latency for the first few packets. This is documented within the DDS specification [35], and QoS can be tuned to attempt to reduce this.

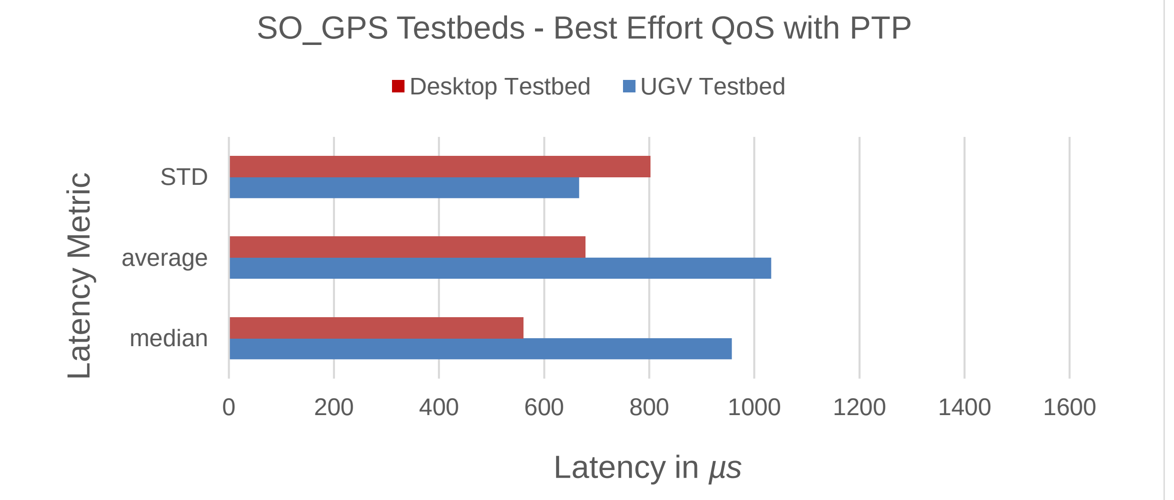
7.6 UGV and Desktop Testbed Latency Measurement Results

The following measurements were taken from the physical UGV testbed / demonstrator platform described in Figure 7.1, (page, 181) and the desktop testbed (Figure 7.3, page 184). SO-Pre-Pro (running in distributed mode) when implemented on the UGV demonstrator platform was running on a Linux PC in a different room from the UGV platform itself, with all nodes connected to the main network via a LAN on the UGV itself. This represents the worst-case scenario for network conditions by having a highly distributed network topology.

The same measurements were also taken from the desktop testbed after the entire testbed was moved from the main UGV demonstrator platform. The nodes are now not separated over a main network and are all attached via the single 10Gb switch on an air gapped LAN. This provides examples of the best-case scenario by being a highly localised network topology.

7.6.1 GPS Sensor Latency to SO Pre Pro – 10000 samples

Figure 7.23 shows the average latency from the GPS sensor generator to SO-Pre-Pro within the UGV testing platform and the desktop testbed. As is perhaps expected we can see an average latency delta of 353.2 μs with the UGV testbed having an increase of 34.2% latency on average over the desktop testbed environment.



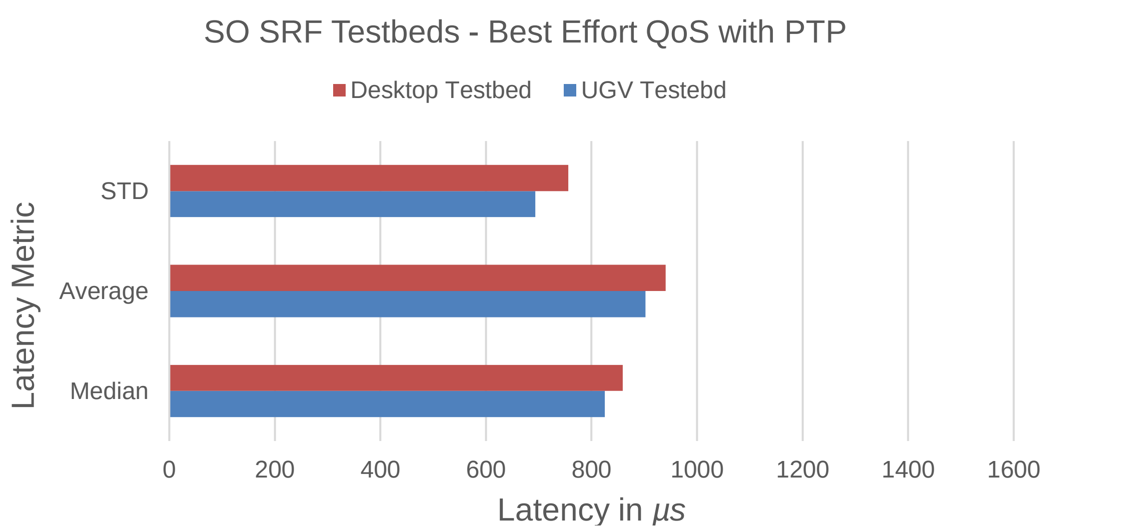
	median	average	STD
Desktop Testbed	560	678	803
UGV Testbed	957	1032	667

Figure 7.23 SO GPS Testbeds - Best Effort QoS with PTP running

7.6.2 Sonic Range Finder Latency to SO Pre Pro – 40000 samples

Within Figure 7.24, we can see there is a 38.3 μs delta between the 2 testbeds with the UGV testbed providing a 4% increase in average latency. This result is the lowest within this set but additionally the sensor data is also the smallest on the wire in terms of bytes sent.

Also, whilst there are 20 sensors as described earlier within this body of work (Chapter 6), each BeagleBone Black has 5 SRF sensors attached to it and sends a single sample containing all 5 sensor readings.

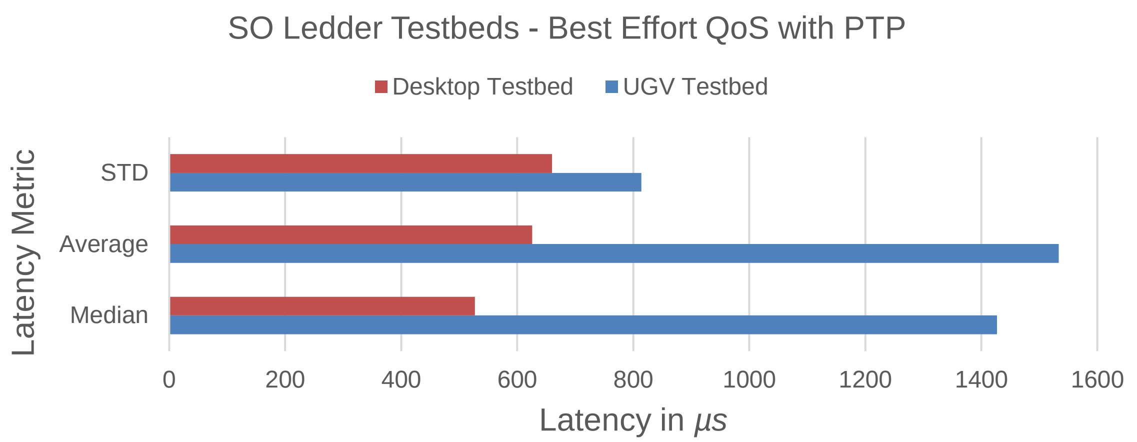


	Median	Average	STD
Desktop Testbed	859	940	756
UGV Testebd	825	902	693

Figure 7.24 SO SRF Testbeds - Best Effort QoS with PTP running

7.6.3 Leddar Sensor Latency to SO_Pre_Pro – 10000 samples – 1 Sensor Node

Figure 7.25 shows the Leddar sensor with a delta of 907.6 μs this presents a 59.1% increase in latency of the UGV testbed over the desktop testbed.

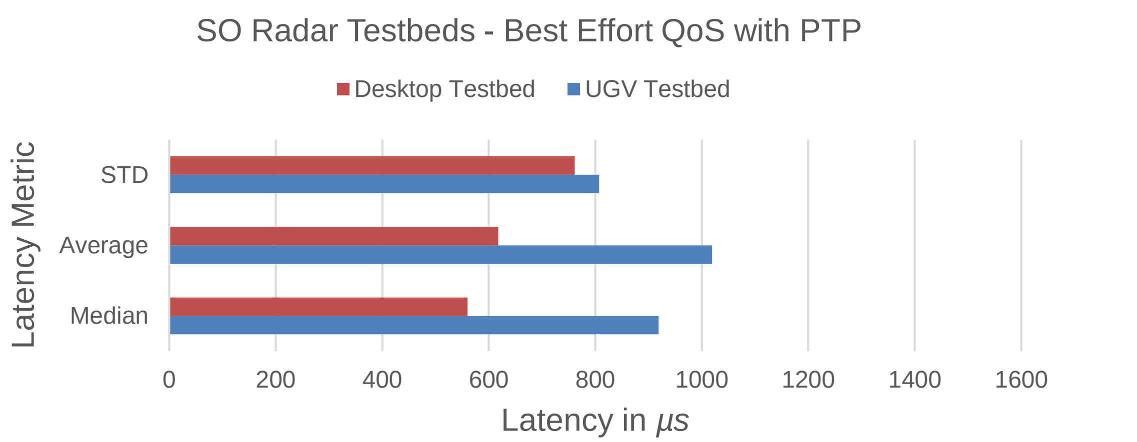


	Median	Average	STD
Desktop Testbed	527	626	660
UGV Testbed	1427	1533	814

Figure 7.25 SO Leddar Testbeds - Best Effort QoS with PTP running

7.6.4 Radar Generator Latency to SO_Pre_Pro – 20000 samples – 3 Sensor Nodes

Figure 7.26, describes the results with a delta of 401.6 μs, creating an increase of 39.3% average latency of the UGV testbed over the desktop testbed.

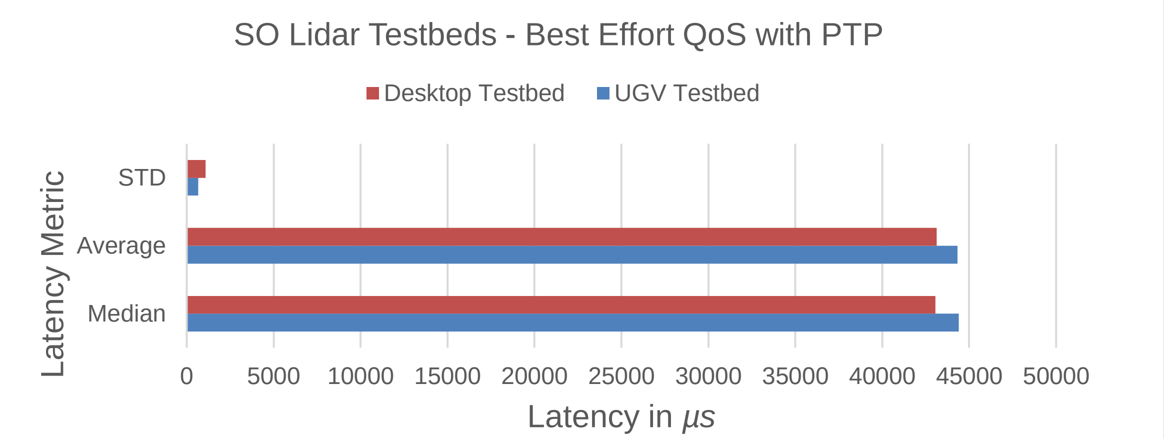


	Median	Average	STD
Desktop Testbed	560	618	761
UGV Testbed	919	1019	808

Figure 7.26 SO Radar Testbeds - Best Effort QoS with PTP running

7.6.5 LIDAR Generator Latency to SO Pre Pro – 10000 samples – 1 Sensor Node

Within Figure 7.27 we can see a delta of 1185.6 which translates into a 2.6% difference in latency, however, the UGV testbed in this case has the lowest latency with the desktop testbed being 2.6% higher on average.

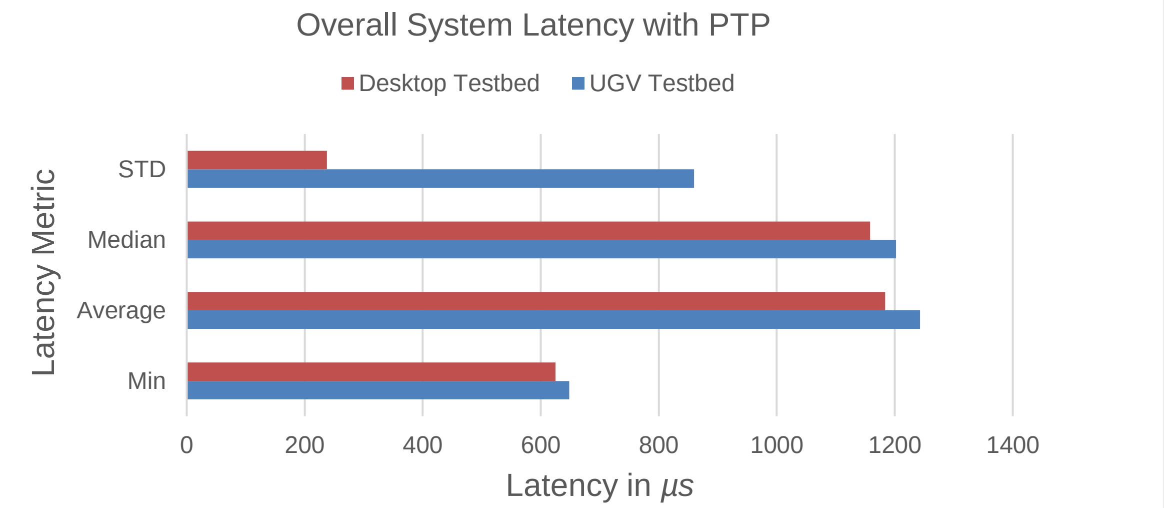


	Median	Average	STD
Desktop Testbed	43057	43136	1093
UGV Testbed	44406	44322	669

Figure 7.27 SO Lidar Testbeds - Best Effort QoS with PTP running

7.6.6 All Sensing Technologies to CMM – 90000 samples

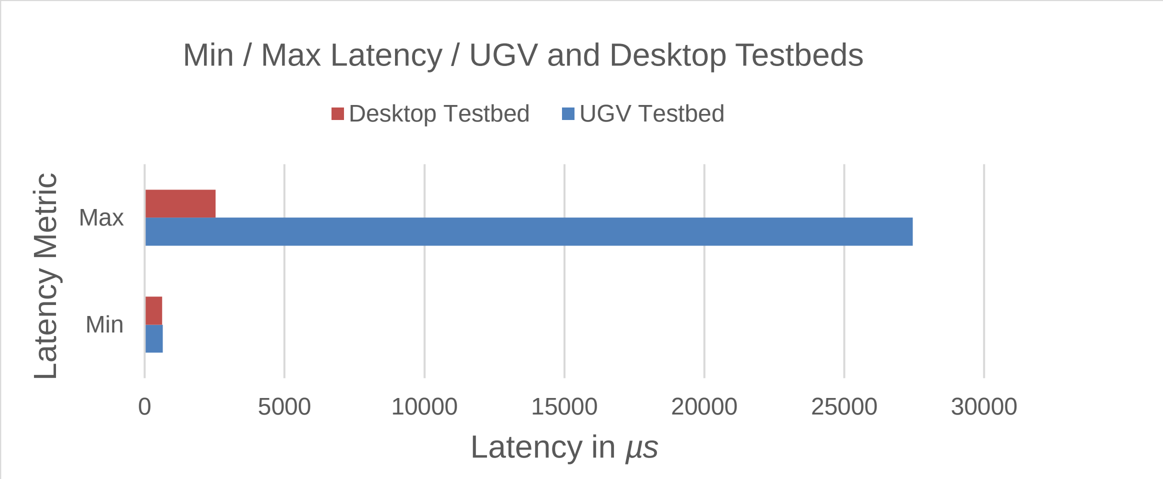
Figure 7.28 shows all sensing technologies publishing simultaneously (Lidar was not being used within these tests as its data bandwidth is not comparable to the other sensing technologies, being much larger). The delta between the 2 results was only 59 μs, with the UGV testbed being 4.7% higher in latency over the desktop testbed.



	Min	Average	Median	STD
Desktop Testbed	625	1184	1158	237
UGV Testbed	648	1243	1202	860

Figure 7.28 Overall System Latency with PTP running

Figure 7.29 shows the minimum and maximum latency of the 2 testbeds. What we can see is that the UGV testbed running on the saturated network has considerably increased (90.7% increase) warm up latency during the discovery phase.



	Min	Max
Desktop Testbed	625	2541
UGV Testbed	648	27453

Figure 7.29 Min / Max Latency / UGV and Desktop Testbeds

7.6.7 Summary UGV Testbed and Desktop Testbed Latency Measurement

This set of measurements was provided to distinguish the difference between an ideal networking environment (Desktop testbed) versus a worst-case scenario of a distributed, saturated network (UGV testbed demonstrator). This is deemed useful due to the real network environments a modern MCS can operate within (damage to network segments resulting in re-routing traffic throughout a vehicle etc.), or in times of heavy network traffic as sub-systems are added to vehicles over time to meet UOR. Or indeed just a normal saturated network backbone within the vehicle. The desktop testbed however is still useful to look at due to the GSFEA being applicable to large, manned land vehicles to small UGVs without the need of modification to the architecture itself.

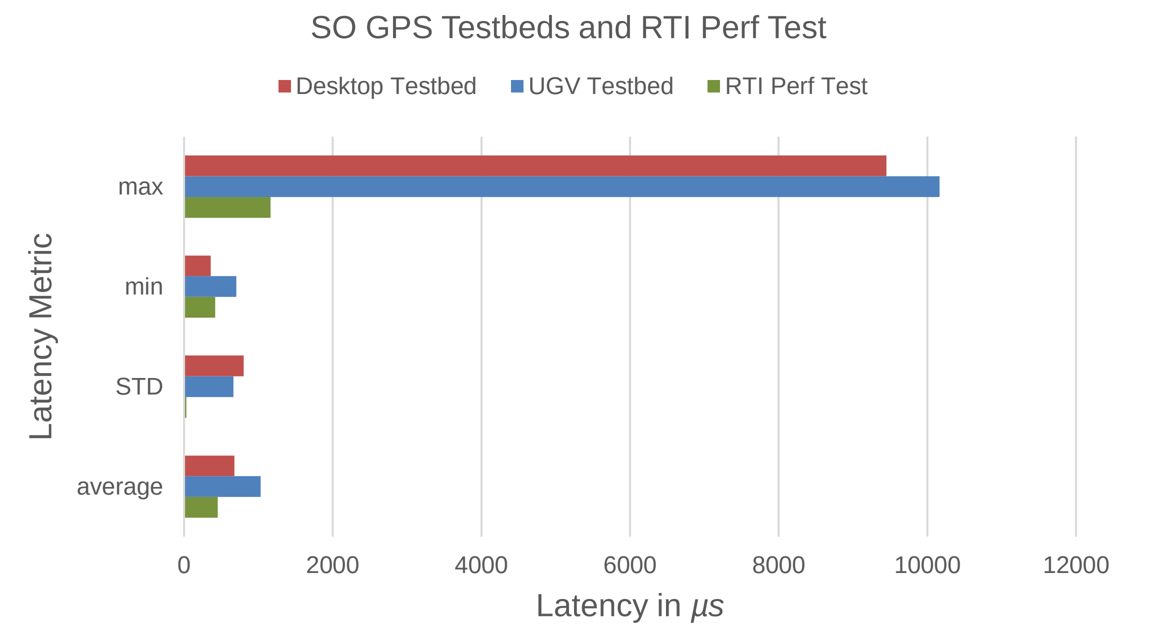
Again, the same parameters are used as for the other measurements taken within this chapter, 10000 samples running on BeagleBone Black V2 and in this case SO-Pre-Pro and the CMM are both running on separate desktop core i7 3rd gen (All Sensing Technologies to CMM – 10000 samples) within each testbed (UGV and Desktop). The difference being of course that the desktop testbed has all nodes connected to the same LAN with only the testbed's traffic on the network. Whereas, the UGV testbed has the SO-Pre-Pro and CMM PC's being elsewhere on the main network within the VRC labs.

7.7 Final Comparative Results

These final sets of results are simply a comparison of the previous results collated together comparing the averages, minimum and maximum latency from all three testing environments (RTI Perf Test tool, UGV testbed and desktop testbed).

7.7.1 GPS Sensor Latency – 10000 samples

Figure 7.30 above shows us there is obviously a large delta between RTI perf test and the UGV Testbed. With a delta of 580 μs a 56.1% increase in latency over RTI Perf Test and a 34.2% increase over the desktop testbed with a delta of 353 μs. However, whilst 34-56% seems significant when we are in the range of 0.001031 millionths of second versus 0.000452 millionths of second the impact on processing time lost whilst waiting for measurements could be described as negligible.

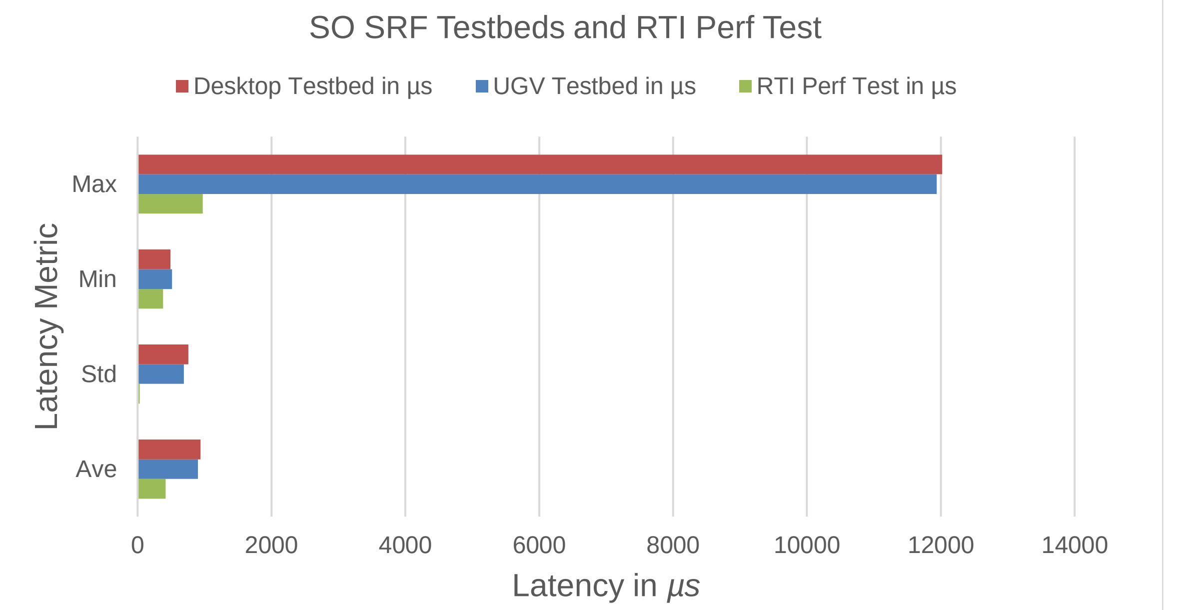


	average	STD	min us	max us
Desktop Testbed	678	803	359	9450
UGV Testbed	1032	666	702	10166
RTI Perf Test	452	29	417	1164

Figure 7.30 SO GPS Comparison between UGV / Desktop Testbeds and RTI Perf Test

7.7.2 Sonic Range Finder Latency – 40000 samples

Within Figure 7.31 we can see similar results as shown in Figure 7.30. With the UGV testbed having an average of 55.5% higher latency over RTIs Perf Test tool with a delta between the averages being 522 *μs.* However, we can see a much smaller delta between the UGV and Desktop testbed being only 38.3 *μs* a 4% increased latency of the UGV platform with the smaller data size of the SRF sensor. Also, again we can see a significant increase in DDS discovery phase, warmup, when looking at the 99.99% maximum latency.

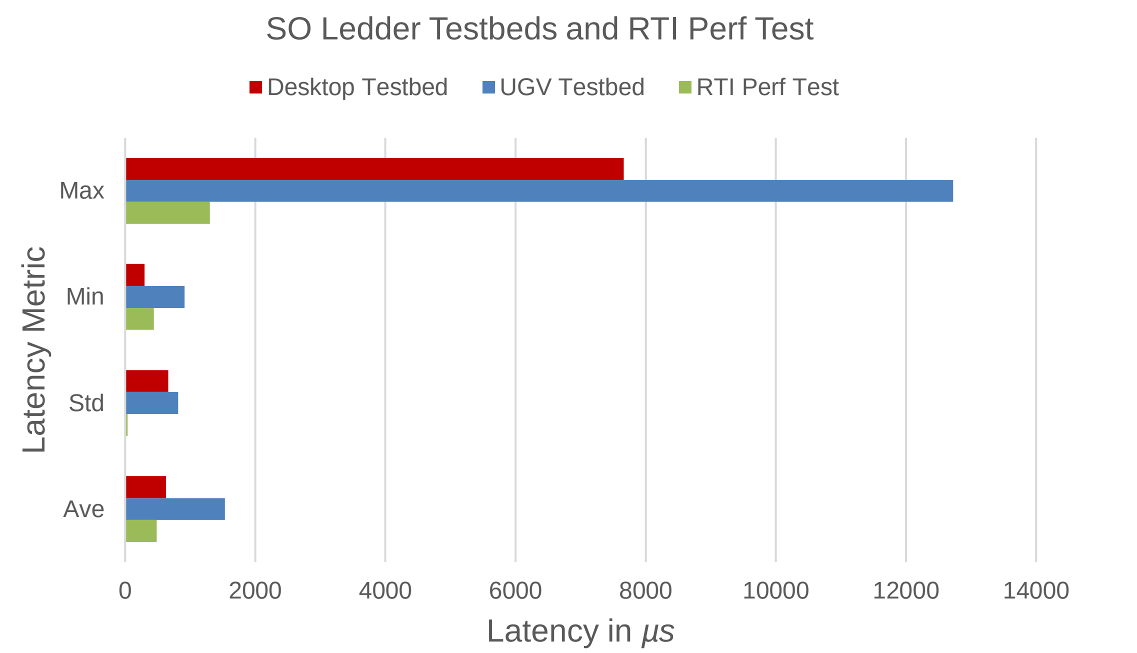


	Ave	Std	Min	Max
Desktop Testbed in μs	940	756	490	12020
UGV Testbed in μs	902	693	514	11941
RTI Perf Test in μs	418	30	383	973

Figure 7.31 SO SRF Comparison between UGV / Desktop Testbeds and RTI Perf Test

7.7.3 Leddar Sensor Latency – 10000 samples – x1 Sensor Node

We can see in Figure 7.32 the delta between the base DDS measurements collected and the UGV testbed being the highest so far at 1050 μs, a 68% increase. The delta between the UGV testbed and desktop being 876 μs a 57% increase. Again, we can see a large delta during the discovery phase with 99.99% messages containing significant delay.

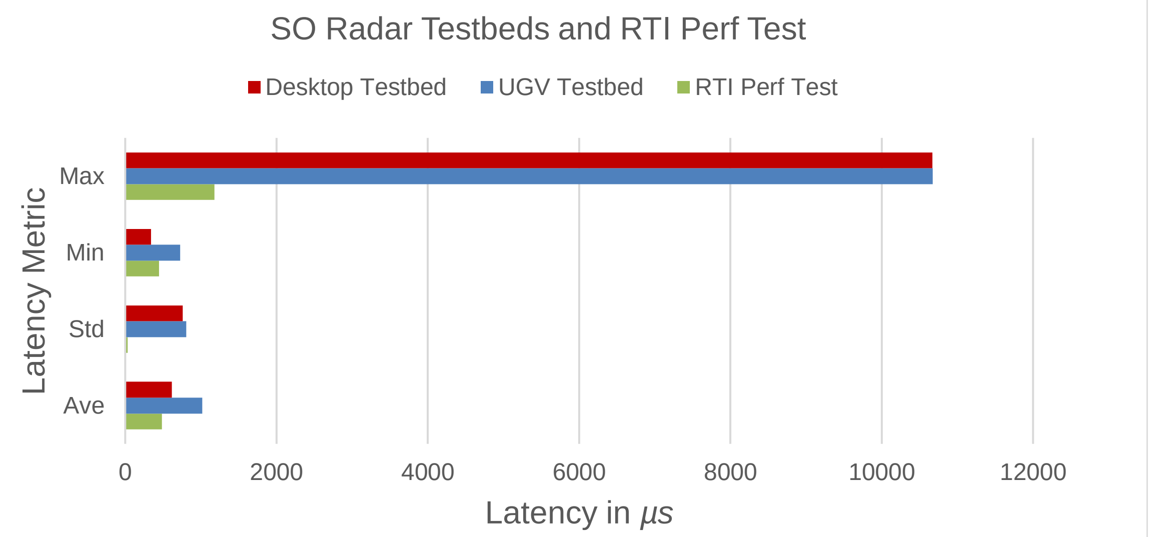


	Ave	Std	Min	Max
Desktop Testbed	626	660	300	7661
UGV Testbed	1533	814	913	12724
RTI Perf Test	483	35	441	1303

Figure 7.32 SO Leddar Comparison between UGV / Desktop Testbeds and RTI Perf Test

7.7.4 Radar Generator Latency – 20000 samples – x2 Sensor Nodes

The Radar generated data samples (Figure 7.33) provide very similar results to the GPS generated samples results. With a delta between the UGV and the RTI perf test being 533 μs, an increase of 53.3%. The difference between the UGV and the desktop testbed being 39.4% with a delta of 402 μs.

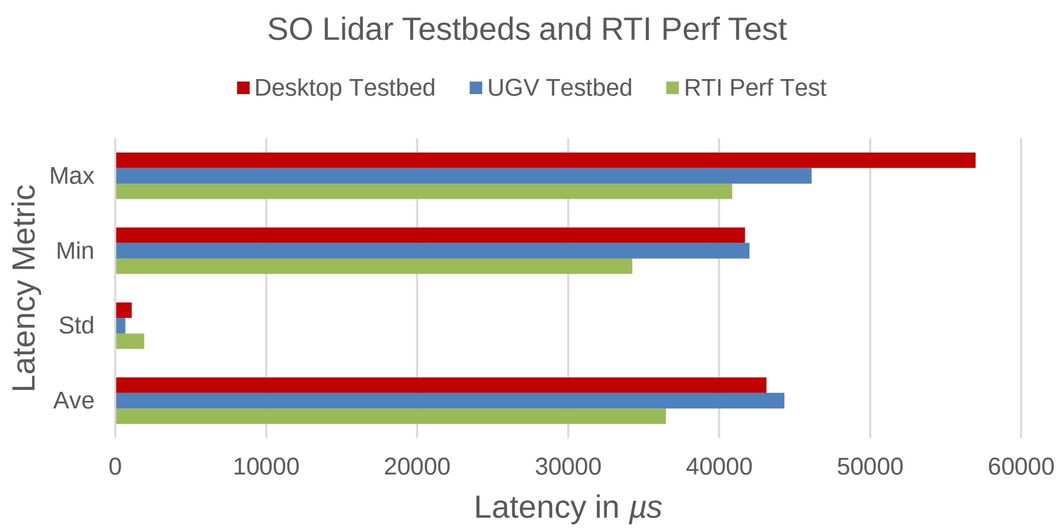


	Ave	Std	Min	Max
Desktop Testbed	618	761	342	10668
UGV Testbed	1019	808	726	10673
RTI Perf Test	486	34	445	1178

Figure 7.33 SO Radar Comparison between UGV / Desktop Testbeds and RTI Perf Test

7.7.5 LIDAR Generator Latency – 10000 samples – Single Sensor Node

Figure 7.34 describes the measurements of the largest data structure within the GSFEA. We see the smallest delta between the UGV and the RTI Perf Tool with a 7842 *µs* being 17.6% increased average latency and a small 2% increase over the desktop testbed with a 1186 *µs.* Given the special case for 3D LiDAR data it would be likely that this data type should be processed at the sensor level and a fused object list should be sent to the CMM rather than the raw data. However, with the architecture design raw data could be selected to be transmitted if required.



	Ave	Std	Min	Max
Desktop Testbed	43136	1093	41714	56996
UGV Testbed	44322	669	42015	46120
RTI Perf Test	36480	1927	34253	40865

Figure 7.34 SO Lidar Comparison between UGV / Desktop Testbeds and RTI Perf Test

7.7.6 Summary of Comparison Desktop to UGV to RTI DDS Perf Tool

This section compares the results for best effort QoS within the UGV testbed, Desktop testbed and RTI Perf Test tool with PTP running. This provides an indication of the overhead from the implementation of GSFEA when utilising DDS. It also provides us of an indication of other factors, such as:

- The differences between best case and worst case for the architecture implementation i.e. GSFEA implemented on a sUGV, LAN, GSFEA implemented on large, mounted combat system,
- The warmup period of DDS discovery when starting the system.

7.8 Conclusion

From the measurements taken we can conclude that the impact of the utilising reliable over best effort could be considered negligible in the overall impact on system latency. However, given that generally you would not require a sensor reading to be resent if not received, the most up to date sensor readings are obviously considered more important. Having IEEE PTP transmitting time synchronisation messages on the same bus produced no significant increase in latency to the DDS messages on the bus, PTP added on average 37 *μs to* overall DDS message latency (shown in section 7.5, p 188 previously). Therefore, it is considered, in latency terms, to be well within acceptable limits and has no concerning impact on the overall system latency.

Obviously, one could state that one of the highest priorities of a sensor fusion system would be to have the highest update rate possible (more updates per second the more accurate the information trying to be ascertained becomes, in this case local environment information). With this being the case, the architecture proposed within this body of work adds an average of 7842 *μs* (in the largest data producer, the LiDAR) to DDS baseline latency captured on the same hardware / network. With the lowest being an average of 522 *μs* latency increase over the DDS baseline test, when looking at the SRF sensing technology. Both measurements are across the architecture to the CMM module.

With this being the case, the measurements captured show the impact on the cycles / updates per second that are required to be achieved for any given application of the architecture on an MCS. Given if you required the sensor fusion architecture to run at 30 Hz (1 update per 0.03333 seconds) or 60 Hz (1 update per 0.01667 seconds) the following describes the impact on tick rate per second from the architecture proposed. The point being to observe how much computational time is left for the fusion process after the messages have been sent and received at the CMM.

The architecture design and the utilisation of DDS impact on system latency:

If you consider the average latency of all the sensing technologies analysed (aside from Lidar) being 1121 *μs*, then one could conclude that the impact on the cycles per second to be minimal. At 30 Hz one, could, on average have available 0.032209000 per second for fusion computation before the next messages would be arriving. However, due to the asynchronization of sensor readings arriving the fusion algorithms would be required to take the next set of temporally aligned sensor readings for fusion processing,

As discussed previously in Chapter 4, 4.2.2, typical 3D Lidar has an update tick of around 10-20 Hz [75], the longest latency time observed ($5.6996 * 10^{\wedge} - 5$ or 0.000056996 seconds), one could argue that you would have to have a separate processing stage for the fusion of the LiDAR data. Likely sending an already fused object list from the LiDAR sensor SO_Pre_Pro stage. Not only would this reduce the processing requirements on the CMM it would also greatly reduce network burden, by sending fused object lists rather than the raw sensor data.

Given the results from this body of work, DDS is considered applicable to sensor fusion within military land platforms to enhance situational awareness by facilitating the integration of COTS sensing technologies. This is discussed in detail within Chapter 8, Conclusion and Future Work.

7.8.1 Enabling Future Capabilities

The testbed (detailed within this chapter) was designed and built to demonstrate the results of this research. The testbed highlighted the benefits of the utilisation of multiple architectures interacting with the GVA environment. These interactions provided not only basic object detection (using multiple ultrasonic sensors, CAN based range finding Leddar sensor and a COTS camera using Open VIVOE) but also, modality of operation and interfaces with future land platform capabilities (such as an Intelligent Digital Assistant (IDA), which was the focus of another Ph.D. students research for a separate DSTL work package).

Figure 7.35 highlights multiple architectures working in harmony with the GVA / NGVA environment to provide the basis for semi-autonomous behaviours.

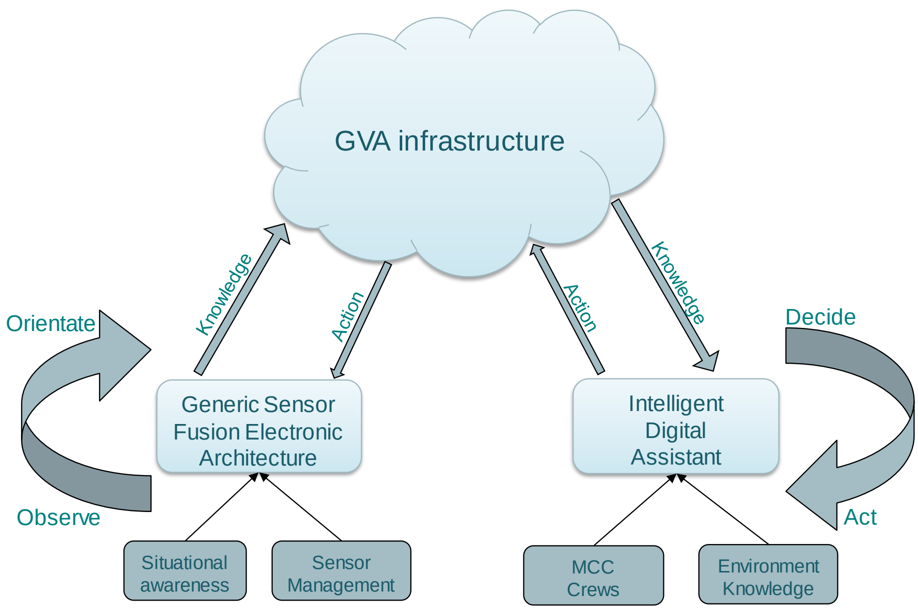


Figure 7.35 Enabling Autonomy within GVA / NGVA

The diagram above describes the Boyd loop [54] effectively coupling multiple logical architectures together providing increased situational awareness for the crews of MCCs.

The discourse of the diagram shows how the entire system is underpinned by the GVA infrastructure allowing sensor management / state and fused sensing data is provided to the vehicles GVA infrastructure (observe and orientate) as knowledge. This is then provided to the crew and other sub-systems within the vehicle (i.e. Intelligent Digital Assistant (IDA), this concept is based on another student's Ph.D. at the request of the UK MoD) where decisions can be made based on the current situation. Information can then be passed back to the GSFEA to provide further actions to be taken based on the current environment / situation, mission tasks at hand (i.e. turn off active sensing, load a different fusion module to identify a specific threat, plan for an emergency route extract, identify tactical mission objectives and so on).

This chapter demonstrated that the proposed Generic Senor Fusion Electronic Architecture can support compatibility with the Defence Standard 23-009 Generic Vehicle Architecture and the STANAG 4754 NATO Generic Vehicle Architecture. It was also shown that, in general, literature states the fusion architecture design must be specific for the vehicle (this is certainly the case for fully autonomous vehicles). However, the results from this body of work support the conclusion that the fusion process is more closely related to the use case not the implementation case.

This is an especially important feature for a basic Local Situational Awareness (LSA) system as it would allow a move toward a plug and play architecture.

However, as the GVA architecture develops with sensor fusion support and further, more complicated use cases will become viable (i.e. semi-autonomous behaviour of platforms, such as UAV / sUGV / mUGV). Plug and play solutions will not likely be viable therefore, plug configure, and play will be the likely, best case, option currently.

8 Conclusion and Future Work

8.1 Conclusions

One current military area of operations is within diverse and complex urban environments, these operating environments can be described as Congested, Cluttered, Contested, Connected and Constrained (the 5C's). Outside the military environment, over the past 10 years significant advances within the automotive sector regarding sensing technologies and autonomous systems have increased exponentially. Driven by enormous investment from the commercial / private automotive Tier 1 and 2 suppliers, with recent years seeing many government sponsored, technology accelerator programs. The results of this significant global investment have produced low cost, advanced, sensing technologies and sensing capabilities, which could potentially be exploited within military land platforms to increase situational awareness.

The contributions of this thesis demonstrated it is possible to take advantage of these rapid advancements of COTS sensing technologies to enhance situational awareness for crews within MCS. Through the utilisation of a novel Generic Sensor Fusion Electronic Architecture (GSFEA) compatible with Def Stan 23-009 Generic Vehicle Architecture (GVA) and STANAG 4754 NATO Generic Vehicle Architecture (NGVA). Also demonstrated was that DDS is viable as a data transfer mechanism for a complex sensor fusion implementation. Hence supporting the potential for improving safety and increasing survivability of MCC, whilst reducing costs to military procurement agencies.

8.2 Thesis Contributions

8.2.1 Analysis for the applicability of COTS sensing technologies within MCS

A wide range of sensing technologies were reviewed, assessed, and categorised with the aim of capturing as many of the requirements as possible. The outcome of this research was used to inform the development of a generic sensor interface architecture and provided a state of art technology watch to identify the benefits and constraints of using DDS for sensor fusion within Mounted Close Combat.

Table 8.1 Benefits, constraints and barriers identified by this research, presents the benefits and constraints (or barriers) identified by this research regarding COTS sensing technology integration into GVA / NGVA compliant military land platforms.

Table 8.1 Benefits, constraints and barriers identified by this research

Benefits	Constraints and barriers

• COTS sensing technologies could be of significant benefit for military land platforms,
• COTS sensing technologies could:
  o Provide enhanced situational awareness to crews of MCC,
  o Be cost effective to procure,
  o Reduce land platform through life costs by promoting market competition and reducing vendor lock in,
  o Reduce time to deployment to meet UOR.
• COTS sensing technologies can be integrated with current DEF Stan 23-009 GVA,
  o COTS sensing technologies offer increased benefit over closed automotive safety sub-systems (i.e. ADAS emergency braking systems),
  o DDS is applicable to sensor fusion, especially within the use cases for military land platforms.
	• COTS technologies could benefit from additional ruggedisation (see future work sub-section 8.4),
	• COTS technologies require additional security considerations,
	• DDS could significantly benefit from software determinism (how to achieve this is partial demonstrated within the IEEE 1588 PTP demonstrated within the thesis),
	• Market competition would likely be against plug and play,
	  o Due to private enterprise preferring proprietary solutions rather than open generic solutions (this is mostly applicable to the sensing nodes but would also apply to the computing nodes), plug and play solutions to meet UOR would likely be difficult to achieve.
	• Sensor fusion is not a COTS product and to achieve COTS sensing technology integration a GVA / NGVA compatible sensor fusion architecture would be required.

8.2.2 Commercial Technology Integration Levels (CTIL)

High level use cases were developed in conjunction with and approved by the UK MoD, these use cases were then used to develop a framework (CTIL) to aid the selection and procurement of any given COTS technologies.

MoD procurement doctrine needs to evolve to meet the speed of deployment of modern threats in an urban environment (i.e. threats purchasing drones from eBay / Amazon and strapping IEDs to them and deploying them, a process sometimes taking only weeks to implement and deploy).

The CTIL framework was then shown to provide procurement agencies for any given scenario that consisted of one or more COTS sensing technologies, an estimate of costs (direct costs and integration costs and time to integrate) versus capability gained.

8.2.3 Generic Sensor Fusion Electronic Architecture (GSFEA)

The GSFEA was developed based on all the previous research contributions within the thesis, it was shown that a GVA / NGVA compatible sensor fusion architecture could be feasible. Utilising DDS throughout which supported some of the functionality offered by the novel modular architecture design.

It was demonstrated that:

- DDS can be applicable to a modular sensor fusion architecture for the GVA / NGVA, considering DDSI-RTPS protocol latency is low enough to support a real time sensor fusion use case,
- Careful consideration needs to be given to the DDS QoS configurations, developing an appropriate QoS profile for each sensor type (to maintain system stability),
- Sensors such as LiDAR need special consideration within the architecture itself as these types of sensors generate large amounts of data per second, again, requiring a tailored DDS QoS profile,
- Attention needs to be paid to the DDS security profile, developing an overall system security profile, to help maintain system integrity,
- Sensor fusion doesn't have to be so tightly coupled in the military domain; it depends on the use case not the implementation case as described predominately throughout past literature. That is, when not being used for autonomous navigation the criticality of a tightly coupled fusion architecture that cannot be altered (i.e. the fusion architecture topology must remain the same, algorithms must remain the same) is not necessarily required.

8.2.4 Generic Sensor Interface Architecture (GSIA)

The Generic Sensor Interface Architecture (GSIA) allows the GSFEA to have a coherent method for the integration of physical sensors. This module supports sensor data collection from the native sensor interface and outputs the data utilising DDS using a generic data model as the software interface. There is currently no Def Stan 23-009 GVA data model supporting COTS sensing technologies.

8.2.5 Capability Management Module (CMM)

Given that the ultimate goal for the integration of COTS sensing technologies is to provide as much modularity and upgradeability as possible; the notion of a fusion modality management module was proposed. This module allowed for the rapid reconfiguration of fusion tasks without the need to redesign the underlying architecture as would normally be the case for autonomous navigation within land vehicles.

8.2.6 Land Systems Remote Gateway (LSRG)

A final core component for achieving land systems integration with future Internet Of Battlefield Things (IOBT) is the management of the remote connection between land systems and off platform systems / vehicles or other LOSA infrastructure. A core requirement is to have a gateway between the land platforms sub-systems and the off-platform communication channels, providing authentication and security for the internal land platform sub-systems.

8.2.7 Generic Sensor Fusion Electronic Architecture Testbed

The GSFEA testbed described within Chapter 7, was critical to demonstrate many of the functions described above and provided a real time, practical insight into the behaviour of the architectural proposition posed in this thesis.

8.2.8 Recommendations and Conclusions Drawn

The following recommendations were provided to the UK MoD at the beginning of 2018, the next VSI project (£3 million, 3-year project) was put for tender (circa late 2018) and contained a large proportion of the recommendations below. Essentially, the call asked for a real-world implementation of a GVA / NGVA compatible sensor fusion architecture, implemented on a real vehicle demonstrator. The aim of the new VSI project was to develop the Generic Sensor Fusion Electronic Architecture itself, and provide a real operational system integrated into a vehicle as a demonstrator / testbed. The Vetronics Research Centre won this VSI contract.

Sensor Fusion – Development of a higher Technology Readiness Level (TRL) sensor fusion testbed to further explore the challenges and solutions identified and presented within this work. This would provide a tool for the exploration of various concepts and ideas, rapidly and cost-effectively within the GVA environment. For example, exploratory research for reducing communication cabling requirements / usage, enhancing the sensor fusion electronic architecture with further research (developing the CMM module functionality for multi model fusion). Additional research should also be carried out to understand security requirements for COTS technologies GVA integration and data modelling for COTS technologies for the GVA environment.

Critical research should also be conducted within such a testbed to develop a GVA harmonised sensor interface/adapter. This is to support the pursuit of the move from plug, configure and play towards plug and play of commercial sensing technologies to take full advantage of a rapidly evolving sensing technology sector.

When exploiting sensing technologies, it is recommended to make use of many sensor types (ultrasound, radar, lidar, camera) as this has many benefits, such as, increasing overall system resiliency and redundancy in the event of sensor damage failure and increasing sensor reading validity. One low level purpose of sensor fusion is to increase sensor reading validity through cross referencing sensor readings with each other before high level inferences (creating knowledge) are made.

Additionally, multiple sensing types complement each other by having contrasting detection behaviours and weaknesses/strengths (e.g. light wave-based technologies such as LiDAR will not detect glass/transparent objects whereas ultrasonic sensors such as parking assist technologies can),

It is also recommended to make use of solid state sensors (no moving parts) such as solid state LiDAR [122], Continental radar (ASR-410) [84]. They offer high reliability within the context of military applications, with near future solid state LiDAR technologies having the additional benefit of likely costing considerably less than their moving parts counterparts [123].

Security and Safety – Considering the publicly available knowledge inherent with commercially available sensing technologies it is critical that security be closely investigated for any technologies being considered for integration into a GVA compliant architecture.

Further research is required investigating methods of mitigating COTS technologies attack vectors when integrated into MCS/GVA environment, it is envisaged that deploying OMG DDS Secure V1.0 [94] could mitigate many of the security issues related to the integration of COTS technologies with DefStan 23-009.

It is recommended that if selecting a specific LiDAR model for deployment that J. Petit's [73] [74] work be understood and the level of this threat be explored for that specific model. As discussed within section 4.2.2 LiDAR Spoofing.

Assessment and research into cost-effective, novel methods of ruggedisation for COTS sensing technologies/ECU (materials and methods) is recommended for exploiting these technologies.

Generic Vehicle Architecture – Further LDM development and additions supporting COTS sensing technologies. It is recommended that the development of an GSFEA is an important addition for future GVA evolution, in preparation for taking advantage of current and rapidly evolving, advanced, COTS technologies/sensing technologies.

Significant benefits of utilising COTS technologies can be achieved by having a long-term strategy/framework towards incorporating/developing a sensor fusion electronic architecture within the context of the GVA environment. Developing such an architecture following the GVA approach allows for modularity and system operational flexibility when integrating COTS technologies into the GVA, along with potentially complex military fusion solutions that meet the operating conditions and taxonomy of the military environment (threat assessment/identification, crew/civilian safety etc.).

8.3 Thesis Real World Impact

Due to the unprecedented global situation over the last few years during the COVID pandemic the completion of this thesis was delayed. This delay in turn provided an unusual insight (for research) into the real-world influence from this body of work. Presented below are examples of this influence either directly or indirectly within the UK MoD Def Stan 23-009 Generic Vehicle Architecture.

8.3.1 IEEE 1588 Precision Time Protocol

Since the completion of this research, PTP has now been included within the Def Stan 23-009 Part 01, Issue 4, published on 14 July 2019 [124].

> "***5.14 Time Synchronisation Services***
>
> ***5.14.1*** *Where the need exists for standard network time synchronisation the time service defined in RFC 5905 must be used. RFC 5905 is a widely used industry standard that defines the protocol, architecture, data structures and algorithms required to synchronise the system clocks of a set of distributed time servers and clients.*
>
> ***5.14.2*** *Where the timing requirements cannot be met by the distribution of time via NTP (RFC 5905), the Precision Time Protocol (IEEE 1588-2008**)** and 1PPS shall be used.*
>
> ***5.14.3*** *The VSI Subsystem Synchronisation study identified that there are a number of approaches to implementing PTP each with advantages and disadvantages. It also provides guidance and requirements that should be considered when implementing PTP, so that a hierarchical scheme is adopted where the timing requirements of the system are matched to a suitable technology. To access a copy of the report please make a request to the GVA Office at desledefstans@mod.gov.uk.*
>
> ***5.14.4*** *Table 13 details the requirements for implementation of time synchronisation services on a GVA Data infrastructure.*

***Table 13 – Time Synchronisation Requirements*"[124]**

Unique Identifier	Priority	Requirement Text
Time Synchronisation		
GVA_INF_71 (Formerly GVA_INF_50)	A	RFC 5905 standard time service for network time shall be used where there is a need for computer network time synchronisation.
GVA_INF_72 (New)	B	High precision timing shall be implemented using Precision Time Protocol (IEEE 1588-2008) and 1PPS
GVA_INF_73 (Formerly GVA_INF_51)	A	Sub-systems shall make use of the common time synchronisation services provided by the GVA Infrastructure.

8.3.2 Dismounted Situational Awareness (DSA)

As described in the operational view presented at the beginning of Chapter 4, Proposed Operational Concept for Military Land Platforms and throughout this body of work, dismounted personnel playing a more significant role within the BMS is being accepted. The necessary digitisation of the battlefield is becoming recognised.

The output of this research highlighted the benefits of a GVA harmonised, bespoke, sensor fusion architecture supporting multiple modes of operation and sensing inputs with dismounts potentially being one of them.

Below is an excerpt from Army HQ website detailing future digitisation for dismounted soldiers, published in April 2021 (accompanied by Figure 8.1).

"*The Army is experimenting with an innovative digital communications suite which will revolutionise the way soldiers operate in the battle spaces of the future.*

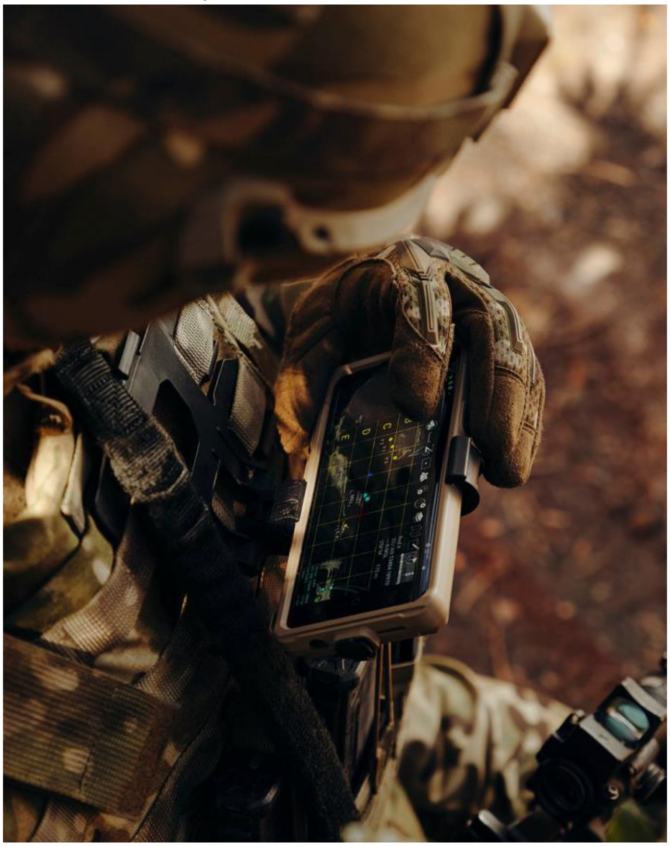


Figure 8.1 Warrant Officer (Class 2) Liam Donnelly utilising the new connected device [125]

Improving their situational awareness or Dismounted Situational Awareness (DSA) is the goal and digital technology is expected to play a vital role in achieving that.

A suite of systems effectively made up of a smartphone, network enabled by the Long-Term Evolution (LTE) network and with a centralised power management component, will shortly be delivered to 2 YORKS, the Enhanced Light Forces Battalion who are currently based in Cyprus to trial.

The unit, marking a change from their previous role as Light Mechanised Infantry, is now spearheading the Enhanced Light Forces role and are the only unit in the British Army to do so, forming the new prototype warfighting and experimentation battalion as part of the Future Soldier transformation plan.

The suite will provide the location of soldiers to commanders with pin-point and real-time accuracy, allowing them to visualise geospatial, picture and message data in a way that until now has only been possible in headquarters locations."[125].

Whilst this concept is not a direct result of this body of work, assumptions can be obviously made that this body of work has contributed to supporting the above concepts viability and importance within future operating environments utilising a GVA style sensor fusion implementation across the entire LOSA family of standards and domains.

8.4 Thesis limitations and Future work

Throughout the course of this body of work the following areas have been identified for future research:

- Security definitions for Mission-Critical systems defining a framework data model approach that gives a clear understanding in security profiles between data,
- Safety criticality for all aspects of the GSFEA, to include real time topology reconfiguration safety cases, CMM multi-mode switching, assurance and validation and safety cases and safety analysis of potential plug and play solutions for sensing technologies,
- Research initiatives for the cost-effective and rapid ruggedisation methods for candidate COTS technologies,
- Further expansion of the GSFEA presented within this thesis, including real world testing of a GVA sensor fusion architecture with fusion algorithms and architecture real time reconfiguration testing, platooning technologies use case (i.e. preparing mounted combat systems for off platform communication and Internet of Battlefield Things (IOBT),
- Expansion and development of the CTIL concept, by analysing, further real-world case studies. Considerable additional research would be required for the assignment of CTIL level to any given technology selected for integration with GVA / NGVA. Human factors should also be considered within future research to be included as part of the CTIL assessment for assignment of CTIL to any given technology,
- Exploring the possibility of using the functional programming paradigm to the sensor fusion components, this could provide the stateless environment for fusion modality switching. Additionally, this should also contain further research into the possibility of enhancing a generic approach and providing simpler upgrade / capability management to meet UOR.

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Appendices

Appendix A: Defence Standard 23-009 Generic Vehicle Architecture requirements

Appendix B: GSFEA Data Model .IDL

Appendix C: Automotive Sensing Technologies examples

Appendix D: Selection of C++ code snippets

10 Appendices

10.1 Appendix A: Defence Standard 23-009 Generic Vehicle Architecture requirements

Table 10.1 Def Stan 23-009 Part 1 Issue 3 requirements group - 1.1.2.3 Messaging [26]

ID	Priority	Requirement Text	Measure of Performance	Justification	Remarks	Verification Method	Verification Description
GVA_INF_52	N/A	**1.1.2.3 Messaging**					
GVA_INF_90	Key	All [sub-systems] shall use the [GVA Data Infrastructure] and messaging protocols for data distribution	[Sub-systems] use the [GVA data infrastructure] for data publishing and subscription between [sub-system] and the [GVA data infrastructure].	[Sub-systems] use the messaging mechanism of the GVA Infrastructure to ensure [vehicle platform] wide access to available data.		Review	Compliance Statement from the Manufacturer, Design Documentation review to check that the GVA [data infrastructure] is used for data distribution.
GVA_INF_53	Key	The interface messaging protocol standards used on a [GVA Data Infrastructure] shall be the OMG Data Distribution Service (DDS) v1.2 and DDS Interoperability Wire Protocol Specification v2.1	Interface shall comply with DDS/DDSI Protocols.	A fundamental requirement underpinning the GVA Approach derived for VSI research activity		Review	Compliance Statement from the Manufacturer, Design Documentation review to check that DDS is used and is in the correct configuration.
GVA_INF_54	Key	DDSI configuration shall be as defined by Section 9.6.1 of OMG Document Number formal/2009-01-05 'The	Compatible with: DefaultMulticastLocator =\LOCATOR_KIND_UDPv4, “239.255.0.1”, PB + DG	An agreed common messaging format between all [subsystems]	DDS defines a datacentric publish subscribe architecture for	Review	Compliance Statement from the Manufacturer, Design

		Real-time Publish-Subscribe Wire Protocol DDSI Wire Protocol Specification'	*domainId + d0\ where PB =Port Base Number = 7400	will allow increased interoperability, portability, and remove closed [subsystem] (vendor lock in)	interconnecting [sub-systems] (composed of data providers and consumers)		Documentation review to check that DDSI is used
ID	Priority	Requirement Text	Measure of Performance	Justification	Remarks	Verification Method	Verification Description
					that promotes loose coupling between these [sub-systems]. A data provider publishes typed dataflows called 'topics', to which data consumers can subscribe.		and is in the correct configuration
GVA_INF_55	Key	The distribution of data on the [GVA Data Infrastructure] shall conform to the GVA Data Model	All publishing of data on to the [GVA Electronic Infrastructure] conforms to the GVA Data Model Where the GVA Data Model does not fully define the interfaces required for the [vehicle platform], any deviations shall be agreed with the GVA Office	The GVA Data Model is used to define all functionality and messaging across the infrastructure		Test, Review	Compliance Statement from the Manufacturer. Delivery of GVA Data Model implementation and conformance testing

10.2 Appendix B: GSFEA Data Model .IDL

10.2.1 GSFEA_Common.idl

This model has been omitted simply because it is very large and is taken from the GVA / NGVA data model with additions to support the GSFEA. All additions from this .idl file can be seen within the following models with GSFEA_Common::

The following were built for use within this thesis:

```
// ***********************************************************************//
//     GSFEA Data Model V10
//
//     Modifications made since the previous data model. Primarily changes
//     to the way versioning is applied have been made. The idl will no
//     contain the version number instead that will be contained within
//     this header. Along with notes of any changes made.
//
//     Version 7 contained adjustments to the naming of the structs due
//     to Matlab only supporting max of 63 chars. Therefore, many of the
//     **PRE_PROCESS typed structs have been modified to **PRE_PRO.
//
//     All structs were changed containing the above for consistency.
//
//     Version 8 contains changes to SRF08_T structs for the ultra sound
//     sensors. Renaming the struct (as may not be the SRF08, could be any
//     ultra sound sensor) and adjusting the struct to contain a sequence
//     for holding 5 discrete SRF04 sensors that run on PRU0 of the BBB.
//
//     Version 9 contains additions for using the kinect device over
//     DDS.
//
//     This version (10) contains a complete re-structuring of the data model
//  beginning with the GSIA component. Moving towards a sensor specific
//     module and a sensor independent module.
//
//  10.4 fixed the keyed data type, rather than being a keyed struct, is
//     a keyed member within each struct
//     (GSFEA_Common::T_SensorObjectGlobalParametersType) for example was creating
//     new instance of a sample due to time data being included. Have now created
//     new time struct containing only time related members based on dateTime type
//
//
//     Author:  Sean Murphy
//     Date:   01/11/2018
//     Version: 10.4
//
//**********************************************************************//

module GSFEA_Common
{

       typedef sequence<string> Tags_t;//@copy // Generic holder for string types.

       enum T_AutomotiveBusType_E
       {
              AUTOMOTIVE_BUS_TYPE__CAN,
              AUTOMOTIVE_BUS_TYPE__CANFD,
              AUTOMOTIVE_BUS_TYPE__J1939,
```

```
        AUTOMOTIVE_BUS_TYPE__FLEXRAY,
        AUTOMOTIVE_BUS_TYPE__LIN,
        AUTOMOTIVE_BUS_TYPE__SPI
};

enum T_SensorStatusReportType_E
{
        SENSOR_STATUS__Error
,
        SENSOR_STATUS__NO_ERROR,
        SENSOR_STATUS__WEAK,
        SENSOR_STATUS__STRONG
};

enum T_SensorSpecificType_E
{
        SENSOR_TYPE__SO_GPS,    //  0
        SENSOR_TYPE__SO_LED,    //  1
        SENSOR_TYPE__SO_LASER,  //  2
        SENSOR_TYPE__SO_RADAR,  //  3
        SENSOR_TYPE__SO_SRF,    //  4
        SENSOR_TYPE__SO_OPTICAL//  5
};

enum T_SensorSpecificParamsType_E
{
        SENSOR_PARAM__POINTCLOUD,
        SENSOR_PARAM__TRACKS,
        SENSOR_PARAM__CENTIMETERS,
        SENSOR_PARAM__METERS,
        SENSOR_PARAM__INCHES,
        SENSOR_PARAM__MILLIMETERS,
        SENSOR_PARAM__OPTICAL,
        SENSOR_PARAM__LONG_LAT
};

enum T_IdentityType
{
        L_IdentityType_Friendly,
        L_IdentityType_Hostile,
        L_IdentityType_Neutral,
        L_IdentityType_Unknown,
        L_IdentityType_Assumed_Friend,
        L_IdentityType_Suspect,
        L_IdentityType_Pending
};

enum T_ObjectType
{
        L_ObjectType_Undefined,
        L_ObjectType_Unknown,
        L_ObjectType_Armour,
        L_ObjectType_Utility,
        L_ObjectType_Infantry,
        L_ObjectType_Engr,
        L_ObjectType_Recce,
        L_ObjectType_Artillery,
        L_ObjectType_Anti_Armour,
        L_ObjectType_Air_Defence,
        L_ObjectType_Air,
        L_ObjectType_Sea,
        L_ObjectType_Installation
```

```
	};

	enum T_ObjectSizeType
	{
		L_ObjectSizeType_Undefined,
		L_ObjectSizeType_Unknown,
		L_ObjectSizeType_Individual,
		L_ObjectSizeType_Team,
		L_ObjectSizeType_Section,
		L_ObjectSizeType_Squad,
		L_ObjectSizeType_Platoon,
		L_ObjectSizeType_Company,
		L_ObjectSizeType_Battalion,
		L_ObjectSizeType_Regiment,
		L_ObjectSizeType_Brigade,
		L_ObjectSizeType_Division,
		L_ObjectSizeType_Corps
	};

	enum T_ObjectOfInterestPriorityType
	{
		L_ObjectOfInterestPriorityType_Unknown,
		L_ObjectOfInterestPriorityType_Low,
		L_ObjectOfInterestPriorityType_Medium,
		L_ObjectOfInterestPriorityType_High
	};

	enum T_PositionAccuracyType
	{
		L_PositionAccuracyType_Low,
		L_PositionAccuracyType_Medium,
		L_PositionAccuracyType_High
	};
};
```

10.2.2 AutomotiveInterfacePSM.idl

```
//********************************************************************//
//	GSFEA Data Model V10
//
//
//
//	Author:  Sean Murphy
//	Date:    01/11/2018
//	Version: 10.4
//
//*******************************************************************//
#include "GSFEA_Common.idl"

module GSIA_Automotive_Interface
{
	typedef sequence <GSFEA_Common::T_Char, 4> T_ShortString;

	struct can_config
	{

		short can_id;
		char can_dl;//@copy /* frame payload length in bytes */
		T_ShortString iface_name;
	};//@top-level false

	struct can_frame
```

```
    {
        can_config can_config_parameters;
        sequence<char, 8> can_payload;
    };//@top-level false

    struct canfd_frame
    {
        can_config can_config_parameters;
        char flags;//@copy   /* additional flags for CAN FD */
        char __res0;//@copy  /* reserved / padding */
        char __res1;//@copy  /* reserved / padding */
        sequence<char, 64> canfd_payload;
    };//@top-level false

    struct CAN_based_message
    {
        short node_ID;//@key
        GSFEA_Common::T_AutomotiveBusType_E CAN_message_type;
        can_frame can_message;
        canfd_frame canfd_message;

        GSFEA_Common::T_TimeServiceType time_of;
    };
};
```

10.2.3 SensorDataFusionPSM.idl

Another large data model taken from the GVA / NGVA data model. Simply to use as is to demonstrate the use of the GVA / NGVA data model within the proposed system. The only structure was the following:

```
    //@copy // AKA Fused Track.
    //@copy //
    //@copy // This forms the primary output of the sensor data fusion algorithm,
implemented by the platform supplier.
    struct C_Object_Of_Interest
    {
        GSFEA_Common::T_IdentifierType A_sourceID; //@key

        GSFEA_Common::T_IdentifierType A_objectOfInterestId;
        GSFEA_Common::T_Coordinate3DType A_position;
        GSFEA_Common::T_PositionAccuracyType A_positionAccuracy;
        GSFEA_Common::T_LinearVelocity3DType A_velocity;
        GSFEA_Common::T_IdentityType A_objectIdentity;
        GSFEA_Common::T_ShortString A_objectLabel;
        T_CallsignType A_callsignOfOriginatingPlatform;
        T_CallsignType A_callsignOfUpdatingPlatform;
        GSFEA_Common::T_ObjectType A_objectDescription;
        GSFEA_Common::T_ObjectSizeType A_objectSize;
        GSFEA_Common::T_ObjectOfInterestPriorityType A_objectPriority;
        GSFEA_Common::T_Boolean A_handedOff;
        GSFEA_Common::T_LongString A_comments;
        GSFEA_Common::T_ShortString A_vehicleRegistrationNumber;
        GSFEA_Common::T_Boolean A_automaticSynchronisationEnabled;
        sequence <GSFEA_Common::T_IdentifierType> A_eventsForObject_sourceID;
        sequence <GSFEA_Common::T_IdentifierType> A_followingSensor_sourceID;
        sequence <GSFEA_Common::T_IdentifierType>
A_synchronisedPeerTargets_sourceID;
```

```
        GSFEA_Common::T_IdentifierType A_localObjectList_sourceID;
        sequence <GSFEA_Common::T_IdentifierType> A_objectDataItems_sourceID;
        GSFEA_Common::T_IdentifierType A_objectOfInterestCP_sourceID;

        GSFEA_Common::T_TimeServiceType time_of;
    };
```

10.2.4 SensorIndependantPSM.idl

```
//********************************************************************//
//      GSFEA Data Model V10
//
//
//
//      Author:  Sean Murphy
//      Date:    01/11/2018
//      Version: 10.4
//
//*******************************************************************//
#include "GSFEA_Common.idl"

module GSIA_Sensor_Independant
{
    //@copy // Included primarily for Lidar type sensor
    //const long MAX_POINTS = 30000;// dont need this here its in common 10.3
compiled with this error though

    struct Sensor_Detected_Object
    {
        GSFEA_Common::T_SensorObjectGlobalParametersType sensor_details;
        GSFEA_Common::T_CivilianIdentityType_E A_civilian_classification;
        GSFEA_Common::T_IdentityType      A_military_classification;

        //@copy // latitude will be sensor reading
        //@copy // longitude will be sensor mount pos
        //@copy // altitude will be height from ground
        GSFEA_Common::T_Coordinate3DType A_position;
        GSFEA_Common::T_LinearVelocity3DType A_velocity;
    };//@top-level false

    struct SO_Tracked_ObjectList
    {
        short node_ID;//@key

        sequence<Sensor_Detected_Object, 64> SO_trackedObjects;

        GSFEA_Common::T_CommandRequestType_E CommandRequest;//@optional
        GSFEA_Common::T_CommandResponseType_E CommandResponse;//@optional

        GSFEA_Common::T_TimeServiceType time_of;
    };

    struct SO_SensorData
    {
        short node_ID;//@key

        GSFEA_Common::T_SensorObjectGlobalParametersType sensor_details;

        sequence<short, 20> SRF_TypeData;//@optional
        sequence <GSFEA_Common::D_LED_TypeSensor, 32> LED_TypeData;//@optional
        sequence <GSFEA_Common::D_EM_TypeSensor, 32> EM_TypeData;//@optional

        GSFEA_Common::D_PtCloud ptCloud;//@optional
```

```
                GSFEA_Common::D_GPS_TypeSensor GPS_TypeData;//@optional
                GSFEA_Common::D_GPS_SatType Sat_TypeData;//@optional

                GSFEA_Common::T_TimeServiceType time_of;
        };
};
```

10.2.5 SensorSpecificPSM.idl

```
//*********************************************************************//
//      GSFEA Data Model VRC Original V10
//
//
//
//      Author:  Sean Murphy
//      Date:    01/11/2018
//      Version: 10.4
//
//********************************************************************//

// notes:
// need to add sensor params
// and sensor type
//*******************************************************************//
#include "GSFEA_Common.idl"

module GSIA_Sensor_Specific
{
        //@copy // Generic Sonic Range Finder data structure.
        struct SO_SRF
        {
                short SensorObject_Node_ID;//@key
                GSFEA_Common::T_SensorObjectGlobalParametersType sensor_details;
                sequence<short, 20> SRF_Distances;

                GSFEA_Common::T_TimeServiceType time_of;
        };

        //@copy // Leddar sensor object
        struct SO_LeddarSensor
        {
                short SensorObject_Node_ID;//@key
                GSFEA_Common::T_SensorObjectGlobalParametersType sensor_details;
                sequence <GSFEA_Common::D_LED_TypeSensor, 32> SegmentsData;

                GSFEA_Common::T_TimeServiceType time_of;
        };

        //@copy // Lidar sensor object.
        struct SO_LidarSensor
        {
                short SensorObject_Node_ID;//@key
                GSFEA_Common::T_SensorObjectGlobalParametersType sensor_details;
                GSFEA_Common::D_PtCloud ptCloud;

                GSFEA_Common::T_TimeServiceType time_of;
        };

        //@copy // Simulated radar sensor contains 20 tracks (tracked objects).
        struct SO_RadarSensor
        {
                short SensorObject_Node_ID;//@key
```

```
                GSFEA_Common::T_SensorObjectGlobalParametersType sensor_details;
                sequence <GSFEA_Common::D_EM_TypeSensor, 32> TracksData;

                GSFEA_Common::T_TimeServiceType time_of;
        };

        //@copy // Generic GPS sensor object.
        struct SO_GPS_Sensor
        {
                short SensorObject_Node_ID;//@key
                GSFEA_Common::T_SensorObjectGlobalParametersType sensor_details;

                GSFEA_Common::D_GPS_TypeSensor GPS_data;
                GSFEA_Common::D_GPS_SatType Sat_data;

                GSFEA_Common::T_TimeServiceType time_of;
        };
};
```

10.3 Appendix C: Automotive Sensing Technologies examples

10.3.1 Continental Technologies

Long Range Radar

Figure 10.1 Continental long-range radar

Measuring Procedure:

The ARS 408-21 sensor measures independently the distance and velocity (Doppler's principle) to objects without reflector in one measuring cycle due basis of FMCW (Frequency Modulated Continuous Wave) with very fast ramps, with a real time scanning of 17/sec. A special feature of the device is the simultaneous measurement of distances up to 250 m, reporting the relative velocity and the angle relation between 2 objects.

Advantages:

Resilience:

The ARS 408-21 radar sensor has the capability to report faults within itself or regarding the readings returned from the environment automatically.

Robust and small design:

By using a radar technology with less complex measuring principle and the development and mass production in automotive supply industry, the design is kept very robust and small.

Interfaces:

The device is fitted with one CAN bus interface. Further interface conversions and software Interface adaptions are available.

Operating Conditions:

Radar operating frequency band acc. ETSI & FCC 76...77 GHz.

Operating-/ storage temperature -40°C...+85°C/-40°C...+90°C.
Life time acc. LV124 part 2 - v1.3 10000 h or 10 years (for passenger cars).
Protection rating ISO 16750 Classification (Trucks).
IP 6k 9k (dust, high-pressure cleaning).
IP 6k7 (10 cm under water), ice-water shock test, salt fog resistant, mixed gas EN 60068-2-60.

Connections:

Monitoring function self-monitoring (fail-safe designed).
Interface up to 8 ID 1 x CAN - high-speed 500 kbit/s.

Housing:

Dimensions/weight W * L * H (mm)/(mass) 137.25 * 90.8 * 30.66/app. 320g.
Material housing front/back cover PBT GF 30 black (BASF-Ultradur B4300G6 LS sw 15073)/AC-47100 (AlSi12Cu1(FE)) die cast aluminium or EN AW 5754 (3.535) AlMg3 pressed-formed aluminium.

Short Range Radar

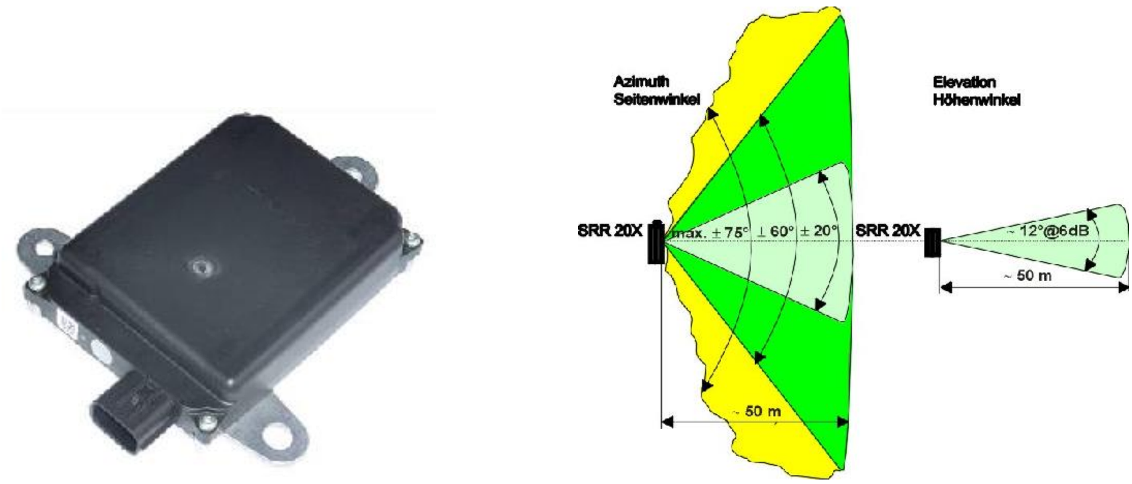

Figure 10.2 Continental short-range radar

Measuring Procedure:

The SRR 2XX sensor measures independently the distance and velocity (Doppler's principle) to objects without reflector in one measuring cycle due basis of PCM (Pulse Compression Modulation) with very fast ramps, with a real time scanning of app 33/sec. A special feature of the device is the simultaneous measurement of distances up to 50 m, reporting the relative velocity and the angle relation between 2 objects.

Advantages:

Resilience:

The SRR 2XX radar sensor has the capability to report faults within itself or regarding the readings returned from the environment automatically.

Robust and small design:

By using a radar technology with less complex measuring principle and the development and mass production in automotive supply industry, the design is kept very robust and small.

Interfaces:

The device is fitted with one CAN bus interface. Further interface conversions and software Interface adaptions are available.

Operating Conditions:

Cycle time >= 33 ms (typical 38 ms)
Radar operating frequency band 24.05..24.25 GHz (ISM band)
Transmission capacity output power app. 18 mW = <12.7 dBm at 200 MHz
Mains power supply typ. 12 V DC +9.0 V...16 V DC full operation >+16 V DC function-permitting (Power Save Mode) >+27 V DC automatic sensor deactivation
Power consumption at 12 V DC app. 4.5 W
High system voltage at 12 V DC up to +27 V DC without time limit
Operating-/ storage temperature -40°C...+85°C/-40°C...+105°C
Shock mechanical 50 g – no mechanical driven components inside
Protection rating IP X9k (high-pressure cleaning), dust, ice-water shock test, salt fog resistant, mixed gas EN 60068-2-60

Displays and Connections:

Monitoring function self-monitoring (fail-safe designed)
Interface 2 x CAN 1, 2 (car, private) - high-speed 500 kbit/s

Housing:

Dimensions/weight W * H * D (mm)/(mass) 155 * 131.5 * 26 (115 * 86 * 26 without fixing clamp)/ 295g
Material housing front/plate rear side PBT-GF30 black coloured (Ultradur)/aluminium pressure die-casting (AlMg)

Miscellaneous:

Measuring principle (Doppler's principle) in one measuring cycle due basis of PCM with very fast ramps independent measurement of distance and velocity
Version SRR 208-2 sensor for the industry open protocol for parameterization and communication
Version SRR 209-2 sensor high sensitivity as SRR 208-2, but with app. 20 dB higher sensitivity
Version SRR 208-2C sensor anti-collision as SRR 208-2, but with anti-collision parameter
Version SRR 208-21 sensor combined functions as SRR 208-2, but with combined functionality

Short Range LiDAR

Figure 10.3 Continental short-range LiDAR

Measuring Procedure:

The rugged SRL 1 sensor from A.D.C. measures the distance to objects without reflector by using the technique of the time of flight with a very high repetition rate. A special feature of the device is the measurement of distance and velocity of multiple objects in 3 independent measuring channels in close-up range up to 13.5 m.

Advantages:

Resilience:

The SRL 1 infrared sensor is equipped with a self-monitoring with a cyclic realized self-diagnosis. Hazard incidents of the sensor will be recognized by itself and displayed automatically.

Efficient:

By using the infrared laser technology and the development and mass production in automotive supply industry, the relation between costs and performance is very good.

Measuring Performance:

Distance range 1.0 – 10.0 m to natural non-reflector targets (standard) 10.0 – 13.5 m expanded distance
Repetition rate 100 Hz
Data read-out time typical 10 ms

Operating Conditions:

Eye safety (time of flight) class 1M laser according IEC 60825-1 1993+A2:2001
Laser power average/laser pulse duration 45 mW/33 ns
Optical peak pulse power max. 80 W at laser source
Wave length 905 nm ±10nm@25°C ± 0.3 nm/K
Operating time/life time min. 12000 hours/15 years
Mains power supply 7.5 - 16 V DC (typical 13.8 V),
120 s protection against wrong polarity
Power consumption < 1.8 W (< 250 mA - typical 130mA@14V)
High system voltage 40 V during 400 ms (disconnection of battery)
Operating-/ storage temperature -40°C…+85°C/-40°C... +95°C
Shock mechanical 100 g, 10 ms, half sine, according IEC 60068-2-27 Ea
Vibration mechanical 40 m/s2 peak@10-60 Hz/20 m/s2 peak@60-200 Hz
Protection rating IP20 (typical mounting behind a windshield)

Connections:

Monitoring function self-diagnostics/permanent self-monitoring of the infrared laser diode
Interface Private CAN – 1 Mbit/s internally terminated with 120 Ω

Housing:

Dimensions/weight W * H * D (mm)/(mass) 150 * 73 * 36/< 100 g

Material housing glass fibre reinforced plastics PA6-GF30, colour RAL 9017 black

Miscellaneous:

Measuring principle T.o.F. Time-of-Flight independent measurement of distance and velocity

Version SRL 1C C = collision avoidance as SRL 1, but with anti-collision switching thresholds

ASL 360

Figure 10.4 Continental ASL 360

The ASL360 Surround View system has great potential to significantly improve road and off-road safety and to reduce fatality statistics, especially within urban scenarios by helping to eradicate blind spots around the vehicle.

Blind spots present significant danger to other people or objects close to the vehicle and limit the users' ability to operate and manoeuvre the vehicle or its machinery safely and effectively. ASL360 is a multi-camera, video DSP-based system designed to provide a view all around the vehicle by combining video from a suite of cameras mounted on the vehicle periphery.

Cameras:

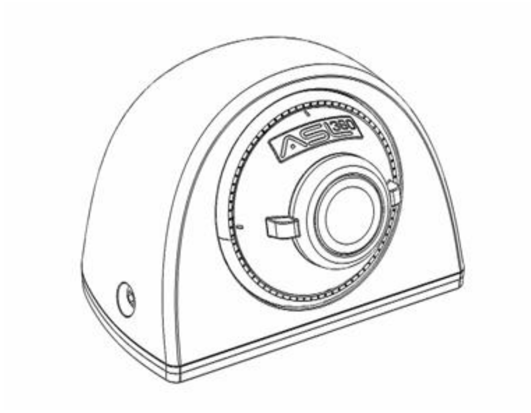

Figure 10.5 Continental ASL360-CM2

The ASL360-CM2 is a wide-angle fisheye camera with IR filter. It has a horizontal field of view exceeding 180 degrees, which allows viewing from horizon to horizon when suitably mounted.

Optical Characteristics:

- Multiple glass element lens
- Aperture F2.0 (nom)
- IR cut coating:
    - 430-620nm, Tmin>80%;
    - 670+/-10nm,T=50%
    - 730-1000nm,Tmax<5%;
- True Horizontal Field of View
    - 185degrees (nom)
- Intrinsic visual parameters calibrated to ~0.2pixels across entire field of view
- Focal range 30cm to ∞

Sensor:

- Sensor size ¼”
- Dynamic range ~75dB
- Signal to Noise ratio 46dB
- Responsivity 16.5 V/lux at 550nm
- Output 720 x 576 (PAL)

Electrical Characteristics:

- Supply Voltage 8V-32V
- Transient protection
- Overvoltage and reverse polarity protection
- Power consumption 0.5W typical
- Cable type Power+TP+LIN
- Connector robust M12 industrial type
- Video output differential

Safety Features:

- Frame counter

Physical Characteristics:

- Ingress IP69K
- Orientable Mount
- ~+/-30degress in all planes and 360degrees line of sight
- Max dimension from base ~48mm

Options:

- Narrow field of view lens
- Matching covers camera

ECU:

Figure 10.6 Continental ECU, ASL 360

The system provides the driver/operator with a real-time, synthesized bird's-eye image of the vehicle using multiple wide-angle cameras typically mounted on the front, sides and rear of the vehicle.

The system is also capable of presenting different views to the driver. If it is desirable that these views are shown automatically without driver initiation, this can be achieved by connecting the ECU's inputs to suitable vehicle signals, e.g.: reverse gear engaged, speed threshold signal etc. It will be necessary to configure the ECU to respond to these signals in the desired manner.

Features:

- 6 camera inputs
- Multiple "screens"
- "Virtual camera" views
- Custom overlays
- Configurable blending
- Natural view roll-off
- Custom User Interface

Electrical Characteristics:

- Supply Voltage 8V-32V
- Transient protection
- Overvoltage and reverse polarity protection

- Power consumption 6W typical
- Camera Cable type Power+TP+LIN
- Camera connectors' robust M12 industrial type
- Video input differential
- Dual Video output
- Video or VGA output
- Inputs from vehicle systems
- Camera comms: LIN

Safety Features:

- Anti-stall
- Low latency

Physical Characteristics:

- Die-cast aluminium case – two mounting points
- 225w x 120d x 35h
- Max cable run >50m

Options:

- IP65 case
- Additional inputs
- Image Processing/ machine vision algorithms

Demonstrable Characteristics:

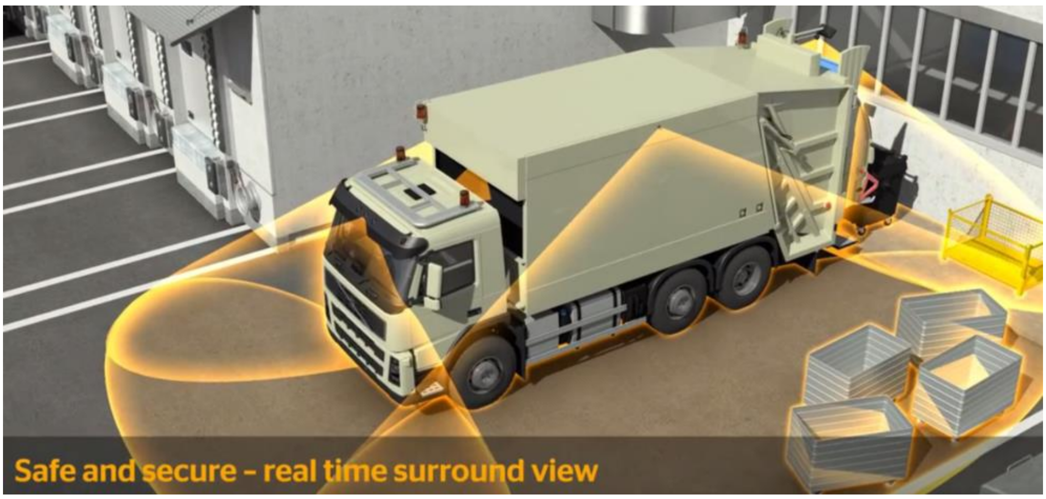

Figure 10.7 Continental ASL 360 surround view

10.3.2 Delphi

Integrated Radar and Camera System

Figure 10.8 Delphi Integrated Radar and camera system

Delphi's industry-first, integrated Radar and Camera System (RACam) combines radar sensing, vision sensing and data fusion in a single sophisticated module. The technology integration is helping to provide optimum value to vehicle manufacturers by enabling a suite of active safety features that includes adaptive cruise control, lane departure warning, forward collision warning, low speed collision mitigation, and autonomous braking for pedestrians and vehicles.

Delphi’s patent-pending RACam uses data fusion algorithms to combine inputs from the radar and camera to reduce the potential for accidents, injury and costly property damage.

Intelligent Forward View Camera (200 Series)

Figure 10.9 Delphi Intelligent Forward View Camera

Delphi's 200 series of the Intelligent Forward View Camera (IFV-200) offers vehicle manufacturers a scalable architecture for their forward-looking safety system needs. The camera is specifically designed to help VMs implement Lane Departure Warning and Forward Collision Warning systems that are New Car Assessment Program (NCAP)-compliant.

Allowing for a customized feature set using common hardware, the IFV-200 uses a single imager and intelligent image processing techniques to provide target classification, robust sensing, and the tracking capability required for multiple safety and convenience functions. Integration of the imager and electronics into a single unit enables multiple safety and convenience enhancements at a lower cost than independent systems.

Components include:

- Complementary metal oxide semi-conductor, high dynamic range (CMOS HDR) camera with high-performance optics.
    - 45-degree horizontal field of view
    - 29 -degree vertical field of view
- Sophisticated image processor
- Mobileye feature algorithms

When fused with Delphi’s multimode electronically scanning radar, the data from the two sensors can be correlated using image processing modules and complex algorithms to further enhance safety.

10.3.3 Mobileye Camera Kit

Figure 10.10 Mobileye camera

The Mobileye Camera Development Kit is perfectly suited for sensor fusion systems, on-road Advanced Driver Assistance and automated driving research. It is similar to Mobileye's EPM (Mobileye EyeQ processing module), which is intended for the evaluation of Mobileye vision applications for automotive mass production. The main difference is that we are offering it for the rest of the world's researchers. The Mobileye 560 system uses a smart digital camera located on the front windshield inside the vehicle.

Inside the camera, Mobileye's powerful EyeQ2® Image Processing Chip provides high-performance real-time image processing, by utilizing the Mobileye vehicle, lane and pedestrian detection technologies to effectively measure and calculate dynamic distances between the vehicle and road objects.

The EyeQ2 Image Processing Chip identifies and sorts the processed images into real-life driving situations, and transmits relevant alerts to the EyeWatch® display and control unit, providing the driver with life-saving alerts.

Figure 10.11 Mobileye vehicle detection

Vehicle Detection:

- Detections on square and rectangular elements at the vehicles' rear
- Detection of the back wheels
- Detection of rear lights at night

Figure 10.12 Mobileye lane detection

Lane Detection:

- Detection of solid or dashed lane markings
- Detection of continuous road markings

Package Contains:

- Mobileye Smart Digital Camera for easy mounting on the windshield
- Connecting Cable
- EyeWatch Display Unit
- Complete Startup and Installation Guide
- Interface Documentation via CANbus
- Direct access to the Mobileye Setup Wizard for system calibration

Max Detection Range:

- Vehicle Day: 150 metres
- Vehicle Night: 90 metres
- Pedestrian (Day Only): 40 metres

Figure 10.13 Mobileye pedestrian detection

Pedestrian Detection:

- Detection of human body characteristics
- Detection of walking motion

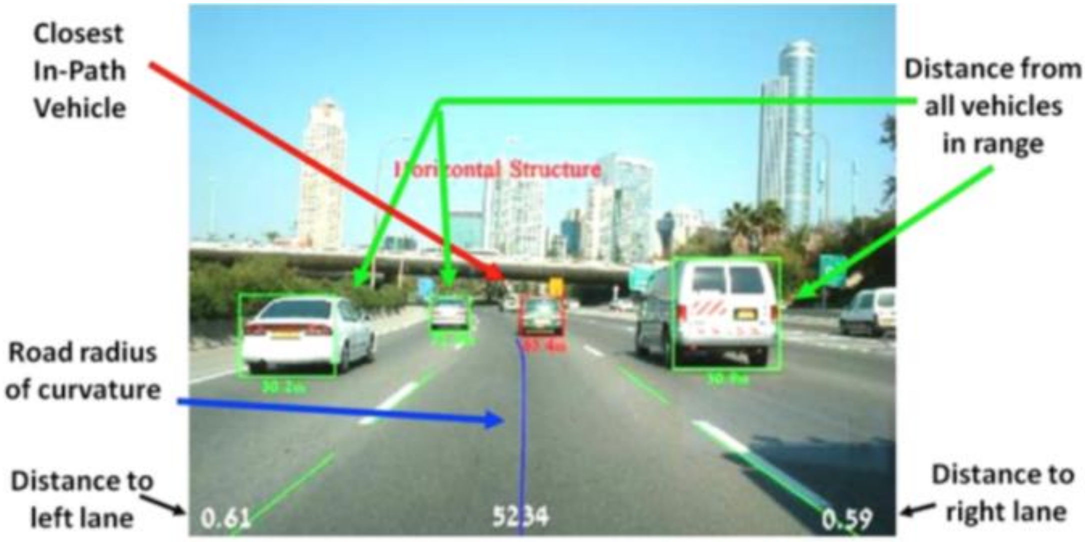

Figure 10.14 Mobile algorithm objects detection

Package Contains:

- Mobileye Smart Digital Camera for easy mounting on the windshield
- Connecting Cable
- EyeWatch Display Unit
- Complete Startup and Installation Guide
- Interface Documentation via CANbus
- Direct access to the Mobileye Setup Wizard for system calibration

Max Detection Range:

- Vehicle Day: 150 metres
- Vehicle Night: 90 metres
- Pedestrian (Day Only): 40 metres

10.3.4 Example of Alternative Parking Assist Technologies

Sensor detection range collision avoidance truck/bus/vans car parking sensor system consisting of the following [92]:

- 0.4m-10m detection parking sensor system suitable for all kinds of trucks, large vehicles, buses, construction machinery, off-road machinery etc. With body over 10 metres;
- LED monitor display Time while driving forward, and detect obstacles distance and direction precisely and display on the LED monitor automatically while reversing;
- Control box with PCABS casing, with waterproof/anti-shock/anti-interference design;
- LED display monitor with built in buzzer alarm or human voice alarm;
- Detachable sensor with water resistant connector, with anti-collision design, with rubber/metal sensor bracket optional;
- Cable: 6PIN waterproof, anti-shock, anti-interference design.

- **Control Box spec:**
    - Rated voltage: 12-48V;
    - Rated Power: <8W;
    - detection range: 0.4 ~ 10m;
    - Display Resolution: 0.1m;
    - Detection angle: single angle 70 ° ± 15 °;
    - Operating Temperature: -40 ° C ~ +80 ° C;
    - Waterproof: IP66;
    - Shockproof: 10G.
- **Sensor detection distance:**
    - Concrete wall: 27.88ft(8.5m);
    - Vehicle: 21.32ft(6.5m);
    - Person: 14.76ft(4.5m);
    - Post (75mm diameter): 9.84ft(3m);
    - Single Sensor detection angle: 80 ° ± 15 ° U/D/L/R;
    - Waterproof rate: IP67;
    - Sensor installation height:1.2M--2.0M;
    - Sensor installation space between two sensors: 0.2M-0.3M;
    - Sensor with metal bracket/rubber bracket optional.
- **Packaging included:**
    - Control box x 1;

- Detachable Sensor x 4;
- 2.25m sensor cable x 4 (3.75m/4.25m optional);
- LED display x 1;
- 10m LED display monitor cable x 1 (10m, 15m, 20m optional);
- 0.5m power cable x 1.

Figure 10.15 Alternative parking assist technologies, ECU and sensors [92]

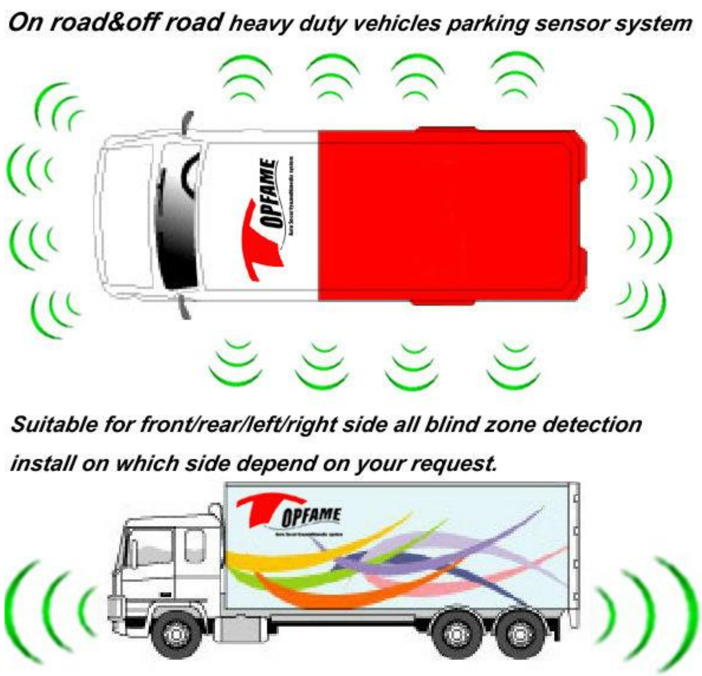

Figure 10.16 Alternative parking assist, sensing example [92]

10.4 Appendix D: Selection of C++ code snippets

10.4.1 pre_pro_dds_entity_manager.cpp snippet

```
/*****************************************************************/
/*  create all high level DDS objects types domain particpant etc. */
/*****************************************************************/
/**
 * @brief dds_entities_manager::dds_entities_manager
 * @param domainID
 */
Pre_Pro_dds_entity_manager::Pre_Pro_dds_entity_manager(int domainID)
{

    /**
      *
      * generic subscriber
      * publisher creation
      * do not remake sub just add typed readers
      * writers
      *
      **/
    // create the domain participant
    participant = DDSTheParticipantFactory->create_participant(
                domainID, DDS_PARTICIPANT_QOS_DEFAULT,
                NULL /* listener */, DDS_STATUS_MASK_NONE);
    if (participant == NULL) {
        printf("create_participant error\n");
        dds_shutdown(participant);
        exit(0);
    };

    // create generic subscriber
    generic_subscriber = participant->create_subscriber(
                DDS_SUBSCRIBER_QOS_DEFAULT, NULL /* listener */,
DDS_STATUS_MASK_NONE);
    if (generic_subscriber == NULL) {
        printf("create_subscriber error\n");
        dds_shutdown(participant);
        exit(0);
    }

    // create generic publisher
    generic_publisher = participant->create_publisher(
                DDS_PUBLISHER_QOS_DEFAULT, NULL /* listener */,
DDS_STATUS_MASK_NONE);
    if (generic_publisher == NULL) {
        printf("create_publisher error\n");
        dds_shutdown(participant);
        exit(0);
    }
}

/**
 * @brief dds_entities_manager::create_publisher_obj
 * @return
 */
int Pre_Pro_dds_entity_manager::create_publisher_obj(int nodeID, char* pubTopicName,
                                                      int print_con)
{

    /** Create publishers **/
```

```
//**********************//
/*     SIM publishers    */
//**********************//
if (distrubted_mode == false) {
    // Register type before creating topic
    SIM_pub_type_name = PUB_TYPE_SUP_1::get_type_name();
    retcode = PUB_TYPE_SUP_1::register_type(
                participant, SIM_pub_type_name);
    if (retcode != DDS_RETCODE_OK) {
        printf("register_type SIM_pub error %d\n", retcode);
        dds_shutdown(participant);
        exit(0);
    }
    // sensor independent module
    // create SIM_pub topic
    SIM_SO_topic = participant->create_topic(
                pubTopicName,
                SIM_pub_type_name, DDS_TOPIC_QOS_DEFAULT, NULL /* listener */,
                DDS_STATUS_MASK_NONE);
    if (SIM_SO_topic == NULL) {
        printf("create_topic SIM_SO_topic error\n");
        dds_shutdown(participant);
        exit(0);
    }

    // create sim writer
    SIM_writer = generic_publisher->create_datawriter(
                SIM_SO_topic, DDS_DATAWRITER_QOS_DEFAULT, NULL /* listener */,
                DDS_STATUS_MASK_NONE);
    if (SIM_writer == NULL) {
        printf("create_datawriter SIM error\n");
        dds_shutdown(participant);
        exit(0);
    }

    // create typed sim writer
    SIM_SO_writer = PUB_TYPE_DW_1::narrow(SIM_writer);
    if (SIM_SO_writer == NULL) {
        printf("SIM DataWriter narrow error\n");
        dds_shutdown(participant);
        exit(0);
    }
} else if (distrubted_mode == true) {
    // sensor tracked object list
    // Register type before creating topic sensor tracked object list
    STOL_pub_type_name = PUB_TYPE_SUP_2::get_type_name();
    retcode = PUB_TYPE_SUP_2::register_type(
                participant, STOL_pub_type_name);
    if (retcode != DDS_RETCODE_OK) {
        printf("register_type STOL_pub error %d\n", retcode);
        dds_shutdown(participant);
        exit(0);
    }

    // create STOL_pub topic
    STOL_SO_topic = participant->create_topic(
                "STOL_TOPIC",
                STOL_pub_type_name, DDS_TOPIC_QOS_DEFAULT, NULL /* listener */,
                DDS_STATUS_MASK_NONE);
    if (STOL_SO_topic == NULL) {
        printf("create_topic STOL_SO_topic error\n");
        dds_shutdown(participant);
```

```
            exit(0);
        }

        // create STOL writer
        STOL_writer = generic_publisher->create_datawriter(
                    STOL_SO_topic, DDS_DATAWRITER_QOS_DEFAULT, NULL /* listener */,
                    DDS_STATUS_MASK_NONE);
        if (STOL_writer == NULL) {
            printf("create_datawriter STOL error\n");
            dds_shutdown(participant);
            exit(0);
        }

        // create typed sim writer
        STOL_SO_writer = PUB_TYPE_DW_2::narrow(STOL_writer);
        if (STOL_SO_writer == NULL) {
            printf("STOL DataWriter narrow error\n");
            dds_shutdown(participant);
            exit(0);
        }
    }
    /* For a data type that has a key, if the same instance is going to be
        written multiple times, initialize the key here
        and register the keyed instance prior to writing */
    /*
        instance_handle = TEST_OUTPUT_LAYER_writer->register_instance(*instance);
         */

    //***********************//
    /*         END          */
    /*     SIM publisher    */
    //**********************//
    return 1;
}

/**
 * @brief dds_entities_manager::create_all_subscribers
 * @return
 */
int Pre_Pro_dds_entity_manager::create_all_subscribers(char* subTopicName,
                                                        int print_con,
                                                        int createChild)//,
SO_DB_Manager* so_db_control)
{
    /** create subscribers **/
//        DDS_DataReaderQos dr_qos;
//        generic_subscriber->get_default_datareader_qos(dr_qos);
//        dr_qos.reliability.kind = DDS_RELIABLE_RELIABILITY_QOS;
//        dr_qos.history.depth = 10;
//        dr_qos.durability.kind = DDS_VOLATILE_DURABILITY_QOS;

    /** new data reader new topic **/
    //***********************//
    /*  SO_GPS typed reader */
    //**********************//
    if (createChild == 1 || createChild == 255) {
        //ofstream resFile;
        //resFile.open("../../results/can-rti-dds-new-dm-no-sec/single-
segment/CAN_rti_dds_100_MonoRaw.csv");
        int gpsCreation = create_gps_reader_and_listener();//, so_db_control);
        if (gpsCreation != 1) {
            std::cout << "gps create error" << std::endl;
```

```
        } else {
            gps_created = true;

        }
    }

    /** new data reader new topic **/
    //***********************//
    /*SO_Leddar typed reader*/
    //**********************//
    if (createChild == 2 || createChild == 255) {

        int leddarCreation = create_leddar_reader_and_listener();//,so_db_control);
        if (leddarCreation != 1) {

            std::cout << "leddar error" << std::endl;
        } else {
            leddar_created = true;
        }
    }

    /** new data reader new topic **/
    //***********************//
    /* SO_Lidar typed reader*/
    //**********************//
    if (createChild == 3 || createChild == 255) {
        int lidarCreation = create_lidar_reader_and_listener();
        if (lidarCreation != 1) {

            std::cout << "lidar create error" << std::endl;
        } else {
            lidar_created = true;
        }
    }

    /** new data reader new topic **/
    //***********************//
    /* SO Radar typed reader*/
    //**********************//
    if (createChild == 4 || createChild == 255) {
        int radarCreation = create_radar_reader_and_listener();//, so_db_control);
        if (radarCreation != 1) {

            std::cout << "radar create error" << std::endl;
        } else {

            radar_created = true;
        }
    }

    /** new data reader new topic **/
    //***********************//
    /* SO_SRF typed reader  */
    //**********************//
    if (createChild == 5 || createChild == 255) {
        int srfCreation = create_srf_reader_and_listener();//, so_db_control);
        if (srfCreation != 1) {

            std::cout << "srf create error" << std::endl;
        } else {

            srf_created = true;
```

```
        }
    }
    return 1;
}


/**************************************************************/
/*  create and destroy individual reader listeners            */
/**************************************************************/

/**
 * @brief SO_pre_processing::create_gps_reader_and_listener
 * @param row
 * @param col
 * @return
 */
int Pre_Pro_dds_entity_manager::create_gps_reader_and_listener()
{

    // Register the type before creating the topic
    SO_sub_type_name = SUB_TYPE_SUP_2::get_type_name();
    // check registered correctly
    retcode = SUB_TYPE_SUP_2::register_type(participant, SO_sub_type_name);
    if (retcode != DDS_RETCODE_OK) {
        printf("register_type SO_Leddar error %d\n", retcode);
        dds_shutdown(participant);
        return -1;
    }

    // create the topic
    SO_topic = participant->create_topic(
                "SO_GPS",
                SO_sub_type_name, DDS_TOPIC_QOS_DEFAULT, NULL /* listener */,
                DDS_STATUS_MASK_NONE);
    if (SO_topic == NULL) {
        printf("create_topic SO_GPS error\n");
        dds_shutdown(participant);
        return -1;
    }

    /* Create a SO_GPS data listener and set row, col for ncurses*/
    SO_GPS_ReaderListener = new SO_GPSListener();

    if (distrubted_mode == false) {

        SO_GPS_ReaderListener->set_sim_typed_writer(this->SIM_SO_writer);
    } else
        if (distrubted_mode == true) {

            SO_GPS_ReaderListener->set_stol_typed_writer(this->STOL_SO_writer);
        }

    // create the SO_Leddar data reader and attach listener
    SO_reader_GPS_type = generic_subscriber->create_datareader(
                SO_topic, /*dr_qos*/DDS_DATAREADER_QOS_DEFAULT,
SO_GPS_ReaderListener,
                DDS_STATUS_MASK_ALL);
    if (SO_reader_GPS_type == NULL) {
        printf("create_datareader SO_GPS error\n");
        dds_shutdown(participant);
        delete SO_GPS_ReaderListener;
        return -1;
```

```
    }

    gps_created = true;

    return 1;
}

/**
 * @brief SO_pre_processing::destroy_gps_listener
 * @return
 */
int Pre_Pro_dds_entity_manager::destroy_gps_listener()
{

    this->SO_reader_GPS_type->delete_contained_entities();
    retcode = this->generic_subscriber->delete_datareader(this->SO_reader_GPS_type);

    if(retcode != DDS_RETCODE_OK) {

        std::cout << "delete DR SO_reader_GPS_type failed in
SO_pre_processing::destroy_gps_listener()" << std::endl;
        return retcode;
    }

    DDSTopicDescription* topicDes = this->participant-
>lookup_topicdescription("SO_GPS");
    DDSTopic* retTopic = DDSTopic::narrow(topicDes);
    retcode = this->participant->delete_topic(retTopic);

    if(retcode != DDS_RETCODE_OK) {

        std::cout << "unregister topic SO_GPS failed in
SO_pre_processing::destroy_gps_listener()" << std::endl;
        return retcode;
    }

    delete SO_GPS_ReaderListener;

    gps_created = false;

    return 1;
}
```