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ETHICS AND ISSUES IN EMBEDDED AND REAL-TIME SOFTWARE ENGINEERING

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ABSTRACT

Embedded and real-time software Engineering is a very important area of study that supports crucial systems in many sectors, like transportation, healthcare, industrial automation, and aerospace. This AI software is implemented with high precision and safety, which makes them reliable and adds good performance. The designing part of this type of system is more than its technicality. The engineer needs to learn about social, ethical, environmental, and regulatory aspects in detail. This study highlights the importance of systems, with an emphasis on professional and ethical obligations that govern their design. It looks into their concerns, like algorithmic bias, data privacy, general regulatory compliance, and sustainability. In this research, a real-life case study, in addition to the Boeing 737 MAX crashes and Volkswagen's emission issues, was evaluated to show the damage of ethical lapses in embedded systems. This aids in reinforcing the importance of ethical design methods by the use of testing, obeying regulatory rules, and sustainability planning in system Implementation. The study suggests a good and forward-thinking solution to the new issues in the industry, which employs development principles that are clear and understandable, supporting interdisciplinary collaboration, and deploying a sustainable framework in the system lifecycle. Furthermore, it explains why accountability, training in ethics, and strong governance are important. The aim is to suggest a guild that not only handles present issues but also prepares real-time system developers for the future needs of this important field.

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Keywords: ADAS, Boeing 737 MAX, Pacemakers, Dieselgate, AOA sensor, MCAS system, AI Bias, Internet of Things Devices (IOT), carbon footprints, GDPR, Modular Programming, ensemble model boosting, Waterfall Model, and radar.

INTRODUCTION

The systems are mainly embedded and real-time software, made to support unique purposes in large electrical systems. Unlike systems that are meant to serve many applications and tasks, prompted by users. Embedded and real-time systems are often resource-constrained in power, memory, processing, and energy utilization; despite this, they are always needed to deliver high efficiency, precision, and high reliability. It is found in microwaves, washing machines, and thermostats, as well as other kinds of modern equipment used in the aerospace, automotive, healthcare, and communication sectors. In this software, embedded systems manage the important part of the operations, like monitoring heart rate in healthcare devices, controlling fuel injection in vehicles, and managing flight surfaces in aircraft, where any malfunction in execution may result in harm.(Marwedel, 2021)

Embedded and real-time system implementation deploys a particular method that balances performance utilization with safety and timing requirements. Software Engineers need to look out for factors like time of execution, use of memory, energy efficiency, and fail-safe principles while adopting compliance with specific standards. The system's times make use of the real-time operating system to control duty scheduling, interrupt management, and allocation of resources, further complicating the engineering process. These embedded and real-time systems have a very important role to play in handling essential infrastructure and devices used every day. Because the business environment where these systems operate is special, it needs a careful engineering approach and a deep knowledge of hardware-software connectivity.AS it keeps expanding in complexity and connectivity, software Engineers are advised to master the technical requirements and learn to navigate ethical, professional, and regulatory issues in the design and deployment phase. (Vahid and Givargis, 2001) In the diagram below shows stages in embedded software design.

An Embedded System Development Process

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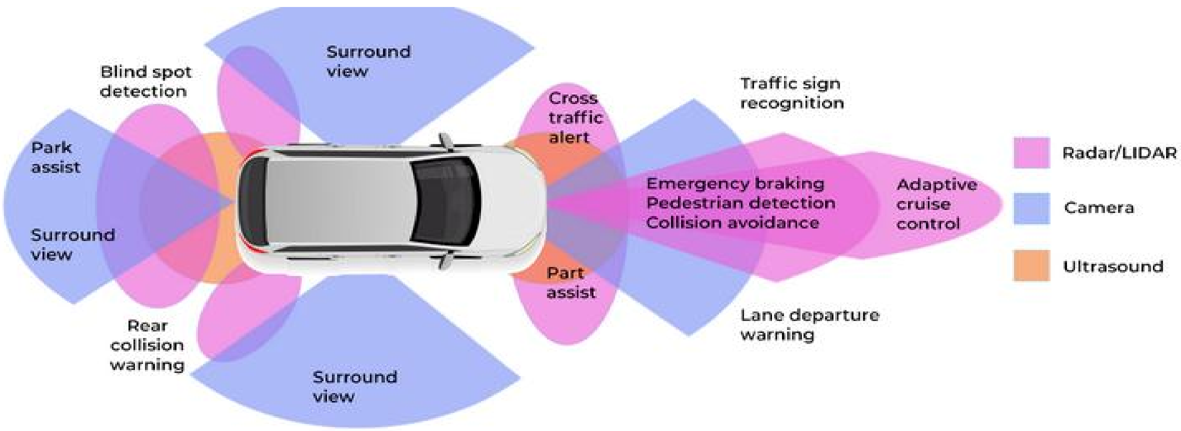
(source:https://sirinsoftware.com/blog/embedded-product-development-from-idea-to-production\)

Related Literature

Applications of Embedded and Real-Time Software Engineering

Automobile

Vehicle functions are controlled by embedded systems, like the timing of the engine, braking, and navigation. Advanced Driver Assistance Systems ADAS in Toyota is a good example. These systems utilize sensors, processors, such as radar, camera, and ultrasound, and software to monitor the surroundings and support, or even automate, driving functions in modern cars.(Immadisetty et al. 2015)

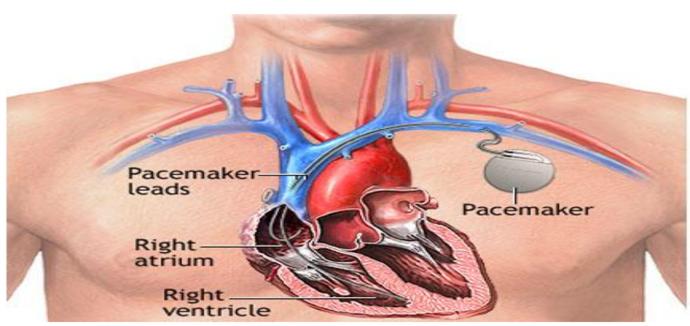


Advanced Driver Assistance System -ADAS

(source:https://www.spiceworks.com/tech/iot/articles/what-is-adas/)

HealthCare

Some equipment, like pacemakers in Figure 3 below, depends on embedded systems to accurately support life-critical operations. This system is capable of monitoring, controlling, and responding to real-time conditions, which ensures that patients are safely monitored and performance is at the optimum level. Embedded software guarantees the accurate delivery of dosage, images accurately, and constant control of the heart's functioning.(Arandia et al.2022)



Pacemaker

(Source:https://www.dranupmahajani.com/pacemaker-implantation.php)

Aerospace

Embedded systems are used in aircraft in fly-by-wire control systems, advanced navigation, engine control, and other onboard safety methods. They are systems that guarantee real-time operation, lessen the workload on the pilot, and improve the stability of the flight. (Zhou and Tan, 2024)

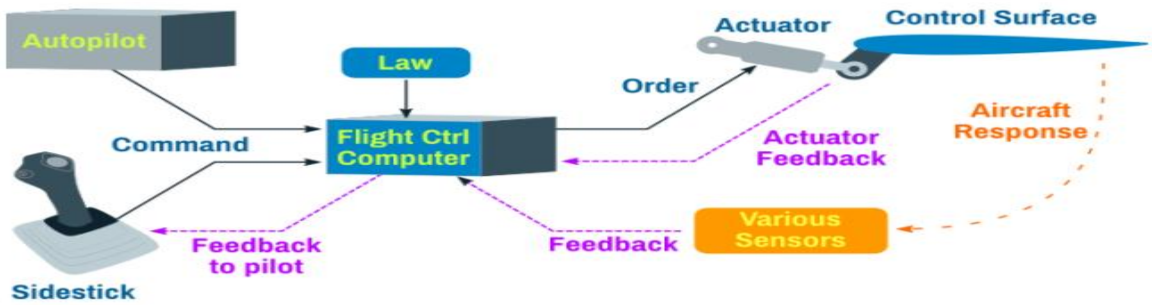
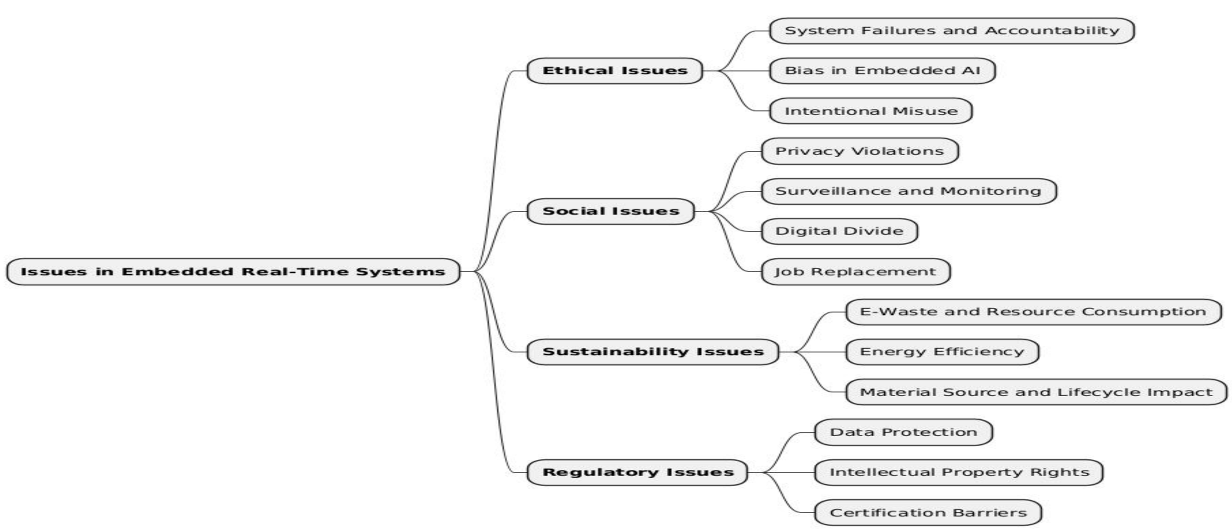


Figure 4 *: Fly-by-Wire*

(source: **https://www.aviation-accidents.net/fly-by-wire-airplanes/**)

Critical Analysis of Issues

It is found through analysis that the combination of embedded and real-time systems can often make it hard to maintain reliability, safety, and quick performance since resources are limited. Some of the difficulties in this area are merging hardware and software, meeting severe time constraints, and dealing with security issues. It is vital to maintain a good response time, consume less power, and keep the system reliable in coping with errors. It is also a constant concern to be ethical and follow regulations in project deployment and development (Diwaker, Chaurasia and Khaliq, 2024) . These are the challenges of embedded and real-time systems, below in Figure 5.



Challenges in embedded and real-Time Systems

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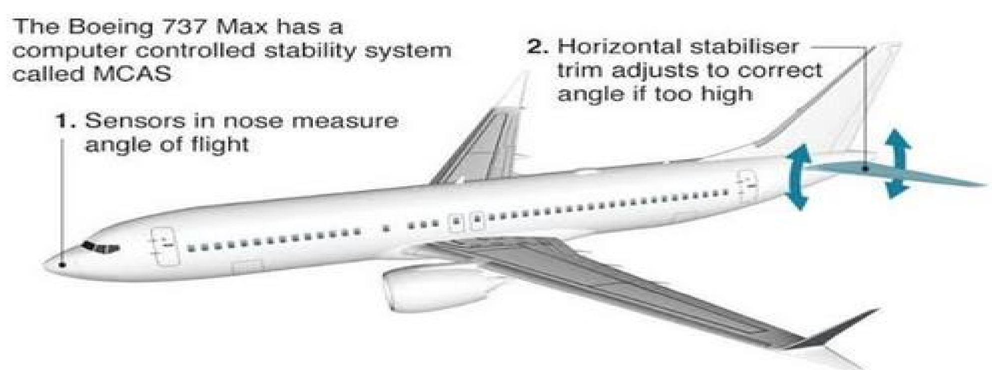
Ethical Issues

The system failure, data privacy, biased algorithms, intentional Misuse and abuses of surveillance or military applications are ethical concerns about embedded systems that demand the responsible conduct of the engineers in the design and testing, and take responsibility.(Sanchez, Brenman and Ye, 2025)

System Failures and Accountability

The fatal Accident of Boeing 737 MAX revealed crucial ethical aspects in which the manufacturers and management were keen on quick deployment rather than safety. This, specifically, has dubious responsibility and regulation, which leads to deadly crashes. Boeing did not follow this principle since it used only one AOA sensor and exposed the plane to the risk of faulty sensors. Having a second AOA sensor and making sure that the two sensors needed to be in agreement prior to the MCAS system being activated would have ensured that the erroneous activation of the system did not happen and led to the crashes. (Thompson, 2024).

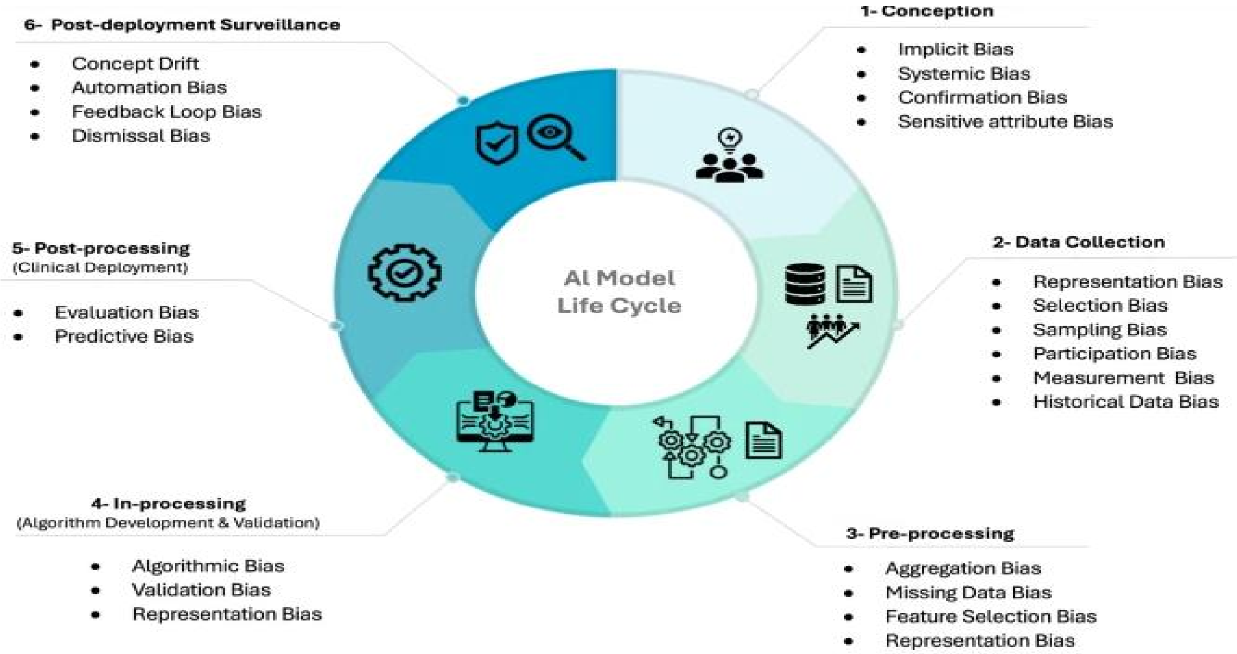


Boeing 737 MAX

(source:https://www.facebook.com/groups/803385438510648/posts/979139930935197)

Bias in Embedded AI

When Embedded Systems are trained on biased data, they can cause misleading and discriminatory results. This raises serious ethical issues regarding equality and justice, making the relevance of various datasets, bias identification, and inclusion in the design principles relevant towards the realization of unbiased AI implementation. In Figure 7 below, two types of AI bias are illustrated in various stages of the AI life cycle,



AI Model and Common biases across each phase

(Source: https://www.nature.com/articles/s41746-025-01503-7)

Intentional Misuse

In the case of the Volkswagen emissions scandal, the company had embedded software that deliberately cheated environmental tests to evade regulations. NOx emissions scandal, or Dieselgate, can be defined as a significant corporate ethics and engineering failure probed in 2015, which involved Volkswagen Group (VW) and some other car manufacturers. This intentional dishonesty points out severe ethical violations, betraying the trust of people, deteriorating the environment, and indicating how improper uses of embedded systems may inflict large-scale social and regulatory losses. (Lauder and Coe, 2024).

Volkswagen emissions scandal-Dieselgate

(Source: https://www.carbonclick.com/news-views/outcome-of-the-nox-emissions-scandal)

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REGULATORY ISSUES

Embedded systems regulatory issues are compliance with data protection, certification offsets startups, and cross-border requirements, which necessitate a strong governance approach, design, and region-based strategies to operate laws and ethics.

Data Protection

To ensure security, user consent, and privacy, engineers should always design embedded systems that handle personal data in a manner that complies with regulations such as the GDPR. When this is not done, appropriate legal action needs to be taken, and penalties will be faced. Proper data control and encryption techniques are very important to achieve legal obligations and protect sensitive personal data effectively.(Raza, et al.2013)

Intellectual Property Rights

In embedded systems, intellectual property rights (IPR) are used to protect the exclusive software code, hardware design, and embedded algorithms. They assist innovators in exercising control over their inventions, blocking unauthorized duplication, and encouraging fair competition. To develop innovation, appropriate management of IPR is crucial, notably in the automotive and aerospace industry and healthcare, where, to an extent, embedded systems take the lead.

Certification Barrier

Although regulatory certifications are necessary to ensure safety and inspire trust, they are major impediments to startups. Innovation and entry to the market may be slowed by the high expense, time commitment, and difficulty of satisfying the standards. Achieving compliance and agility is possible with minimal processes and support systems that will promote responsible innovation without crushing progress.(Broy *et al.,* 2007)

Real-Life Event for Sustainability Issues

Automotive Emissions Scandal (“Dieselgate”, 2015)

- The Volkswagen software installed in diesel vehicles was meant to cheat during the tests by issuing a signal that a test was going on and lowering the car's emissions temporarily.
- It destroyed a company as regulatory authorities (the EPA in the United States, their counterparts in the rest of the world) discovered the ruse, imposed huge fines, and recalls.

Methods and results

This particular Concept in embedded and real-time software Engineering has to do with creating or designing innovative, practical solutions to ethical challenges. It also involves coming up with a system that is fault-tolerant, predictive maintenance utilizing AI, and modular programming to ensure scalability and flexibility. Developers/Engineers have to deal with limitations such as limited resources, time, and safety-critical. Model-based design solutions, simulation, and hardware-in-the-loop testing enhance the accuracy and reliability of development. Also,

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responsible innovation should be supported by integrating ethical concerns (privacy, security, and sustainability) in the design process.(Henzinger and Sifakis, 2006)

Rationale for Proposed Solution

- To stop fatal Damages because of software failures
- To give the general public good expectations and maintain their trust
- To make sure that the legal requirements are met to avoid a penalty
- To enhance the promotion of good technology and reduce negative environmental impact
- To make sure that the right method for AI bias prevention is implemented during software development.

Critical Analysis of Professional Standards/Framework

Standards are mutually accepted rules, guidelines, or specifications adopted by organizations or governing bodies like the International Standard Organization (ISO) to achieve such things as quality, safety, interoperability, consistency, and compliance with production, processes, and services. Below is the table of the critical analysis of the professional standard in this work.

Critical Analysis of Professional Standards /Framework

Aspect	**Standards/Framework**	**Purpose & Ethical Relevance**	**Critical Analysis & Real-Life References**
Automotive Functional Safety	ISO 26262	Deals with the safety of embedded systems in the automotive industry, focusing on the safety lifecycle and hazard analysis.	Encourages safety in such systems as ADAS. Moral slips (unintended acceleration of Toyota or Dieselgate of Volkswagen)
Medical Service Lifecycle	IEC 62304	Ensures safety, risk management, and lifecycle documentation of health-critical devices	Scale trustworthy pacemakers and infusion bottles. There is an ethical significance of not having failure, putting human lives in danger (as mentioned in Section 2.2).
Aerospace safety-critical Software	DO-178C	Supplies certification and test considerations	Boeing 737 MAX crash: the inability to comply

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		of airborne embedded systems.	with the appropriate standards of software testing and redundancy
Ethically aligned design (AI software)	IEEE 7000 series	Incorporates ethics in the development and construction of AI	Minimizes discrimination within such mechanisms as facial recognition (e.g., IBM, Amazon).
Regulatory Compliance	GDPR	Ensures the privacy of the user, regulates the handling of data of the embedded systems.	Access control, enforced encryption, and transparency have to be put in place in real-time systems. The consequences of non-compliance may lead to legal and ethical breaches (e.g., the VTech hacking incident).
Intellectual Property and License	Copyright patents, open-source licensing (GPL.MIT)	Offers security to software developers and directs the legal usage of third-party/ components	The application of embedded systems has to steer clear of IP violation during firmware/software re-use. They are required to honor open-source licensing (e.g., GPL libraries)

Case Study: The Boeing 737 MAX Crashes-An Ethical and Systemic Failure: Tragedy in Embedded System Design.

- It has a close association with embedded and real-time system failures.
- It reveals ethical design and regulatory, testing, and corporate accountability lapses.

Unsuitable Paradigms

- Waterfall Model: Not flexible enough to be used with embedded systems that need to go through an iterative process of testing as well as validation.

- Code-First Development: It creates systems that are not robust because code-first development takes place without any analysis of the requirements and the risk involved.

Observations

The combination of ethical steps and safety standards in embedded and real-time software engineering plays a very important role in ensuring software accountability, reliability, and users' trust. BY adopting development processes with widely recognized frameworks like the IEEE 700 series, IEC 62304, DO-178c, and ISO 26262, Safety, Security, and ethical issues can be easily addressed by developers and engineers. Adding fail-safe strategies, a robust error-handling mechanism lowers the chances of failures that are deadly, mainly in mission-critical applications. model-based design and validation strategies that can be implemented will allow the flaws of the design to be detected early, and will improve the correctness of the software in various conditions before deployment.

Summary

Embedded and real-time software systems are critically analyzed in this work with comments made with respect to the challenges, which are ethical, social, sustainability, and regulatory. It looks at real-life case studies such as Boeing 737 MAX crashes to show the disastrous outcomes of poor design, systems, transparency, and poor regulation. The article is a critique of the inappropriate paradigms of development, such as the Waterfall and code-first paradigms in safety-critical software. Surveillance, digital inequality, and e-waste are also discussed in it. The suggestions are to include the iterative design, ethical compliance, and following the international standards on safety in the future to enhance embedded systems.

Recommendation for Future Practice

- Require training of engineers on ethics.
- Use of the right methods like monitoring, ensemble model boosting, etc., to prevent Bias
- Implement an independent safety-critical system audit.
- Encourage the development of green engineering by policy incentives.
- Encourage the extended life cycle of goods and products that can be upgraded.
- Invest in recyclable and low-power hardware technologies.

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