Concepts for Steering Wheel Hands-off-detection

Master's Thesis in Product Development

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Master's thesis 2026

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Cover: A simplified wooden steering wheel inspired by a ship's wheel, presented in a minimalist composition.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2026

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Abstract

The growing deployment of Level 2 and Level 3 automated driving systems in automotive applications, particularly in passenger cars and commercial vehicles, has increased the importance of reliable driver monitoring. This is especially relevant in situations where the driver must remain engaged and be ready to retake control when necessary. In this context, steering wheel hands-on/hands-off detection (HOD) plays a key role in determining whether the driver maintains physical contact with the steering wheel. Currently, many HOD systems are based on capacitive sensing integrated into the steering wheel. While this approach is widely adopted in current advanced driver assistance systems (ADAS), it is associated with several practical limitations, including sensitivity to environmental influences, reduced performance when gloves are worn, dependence on hand placement, and challenges in achieving consistent robustness under real driving conditions.

To address these limitations, this thesis explores alternative concepts for steering wheel hands-off detection by examining sensing technologies used in related engineering domains. A cross-domain review is conducted covering robotics, industrial automation, medical devices, and aviation, with the aim of identifying sensing principles that may be transferable to automotive applications. The selected technologies are assessed using criteria such as detection reliability, feasibility of integration, safety relevance, environmental robustness, cost, and compatibility with automotive requirements.

To support the concept evaluation, an exploratory Proof of Concept (PoC) was developed to demonstrate selected sensing principles and assess their practical feasibility in a steering wheel context.

The study highlights several promising sensing approaches that could either replace or complement existing capacitive systems. By providing a structured comparison of cross-domain technologies and an evaluation of their suitability for automotive use, the thesis offers a foundation for future development of more reliable HOD solutions. Ultimately, the work contributes to improved vehicle safety, more dependable ADAS functionality, and the continued advancement of human–machine interaction in automated driving.

Keywords: HOD, ADAS, Alternative sensing technologies, Functional Safety, Sensor Fusion

Acknowledgements

We would like to sincerely thank everyone who supported us throughout this thesis work.

We are especially grateful to Erik Skoglund for the opportunity and encouragement to carry out this thesis at Volvo Cars.

We would also like to thank Levent Aliustaoglu and Alejandro Pradas Gómez for their guidance, valuable feedback, and continuous support during this study.

In addition, I would like to thank Ebru Turanoglu Bekar for the constructive academic feedback provided during this work.

Rushikesh Kudale & Wen Zhou, Gothenburg, June 2026

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis:

HOD	Hands-on/Hands-off Detection
ADAS	Advanced Driver Assistance System
SAE	Society of Automotive Engineers
DMS	Driver Monitoring Systems
OEM	Original Equipment Manufacturer
PoC	Proof of Concept
HO	Hands-On
HOF	Hands-Off
RF	Radio Frequency
HMI	Human Machine Interface
SUVs	Sports Utility Vehicles
STW	Steering Wheel
EMI	Electromagnetic Interference
ESD	Electrostatic Discharge
EPS	Electric Power Steering
ECU	Electronic Control Unit
SFCS	Swept Frequency Capacitive Sensing
ADC	Analog-to-Digital Converter

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Introduction

1.1 Background

Steering wheel hands-on/hands-off detection is an important function in modern advanced driver assistance systems (ADAS) and semi-autonomous driving. In Level 2 and Level 3 driving scenarios, the driver may be supported by automated functions but is still expected to remain engaged and ready to retake control when required. Therefore, detecting whether the driver's hands are on or off the steering wheel, and how the driver interacts with the wheel through touch or grip, is relevant for maintaining safe driver–vehicle interaction.

In today's automotive industry, steering wheel hands-on/hands-off detection is generally considered a mature and industrialized function, with similar technical approaches widely adopted across OEMs and established for large-scale deployment. However, while existing solutions are not incorrect, the diversity of sensing principles applied to this function appears limited compared with sensing technologies used in other industries, and practical challenges have been found under real-world conditions. This motivates the exploration of alternative sensing solutions for potential future development.

Within this broader background, this thesis is conducted in collaboration with Volvo Cars, within the Occupant Safety and Steering Wheel development area. The thesis explores alternative concepts for detecting whether the driver's hands are on or off the steering wheel, and how the driver holds or interacts with the steering wheel.

1.2 Problem Statement

As Level 2 and Level 3 automated driving systems become more common, the need to monitor driver engagement has increased. In the SAE automation taxonomy, Level 2 refers to partial driving automation where the system can support both lateral and longitudinal vehicle control, but the driver remains responsible for supervision. Level 3 refers to conditional driving automation, where the system can perform the driving task within a defined operational design domain, but the driver must be available to respond to a takeover request when required [4]. In this context, advanced driver assistance systems (ADAS) rely on driver-monitoring functions to support safe interaction between the driver and the automated system.

One relevant driver-monitoring function is steering wheel hands-on/hands-off detection (HOD), which determines whether the driver's hands are in contact with, or sufficiently interacting with, the steering wheel. ISO/PAS 11585:2023 refers to hands-on/off detection on the steering wheel as one part of the driver-monitoring system in the context of supervised partial driving automation [5]. In current automotive applications, a common HOD implementation is based on capacitive sensing mats integrated under the steering wheel surface. These sensors detect changes in capacitance caused by the presence or contact of the driver's hand near the sensing area. However, capacitive HOD can be affected by real-world use conditions, such as gloves, moisture, temperature variation, hand placement, metallic objects, or external attachments. These limitations may reduce detection robustness and can affect the reliability of the HOD input used by ADAS functions.

Other engineering fields, such as robotics, industrial automation, medical engineering, and aviation, make use of alternative sensing and detection technologies that may offer improvements. Despite this, cross-industry exploration has not been systematically conducted for its potential application in automotive steering wheel hands-off detection in Volvo Cars.

Therefore, the problem addressed in this thesis is the lack of a structured investigation into the alternative sensing solutions or concepts for HOD that could overcome the limitations of the existing capacitive based sensing system. This thesis aims to explore and evaluate relevant alternative sensing technologies from the adjacent domains and assess their suitability for automotive integration.

1.3 Purpose

The purpose of this master thesis is to explore and assess alternative sensing technologies or solutions for steering wheel hands-on/hands-off detection from a engineering perspective. As well as finding possible sensor combination under sensor fusion scenario. While existing automotive solutions are already mature, the project does not aim to improve or optimize the current solutions; instead, it investigates whether sensing technologies originating from other domains can offer different perspectives. That is, We are aiming to investigate into different industry domains and scientific research to identify sensing solutions that address similar functional requirements (e.g., detecting human presence, contact, or interaction) and analyze them in a systematic approach.

1.4 Research Questions

The following research questions have been developed to guide the thesis work in a structured manner and to address the stated problem.

RQ-01: What alternative sensing technologies currently exist that could potentially support the steering wheel hands-on/hands-off detection?

RQ-01.1: What evaluation/screening criteria should be used to assess candidate sensing solutions for steering wheel hands-on/hands-off detection?

RQ-01.2: Which sensing solutions appear most promising for further investigation, and why?

RQ-02: How can a multi-sensing approach improve the robustness of steering wheel hands-on/hands-off detection?

RQ-02.1: Which sensing technologies can complement each others to overcome the limitations of individual HOD sensing methods?

1.5 Scope and Delimitation

The scope of this thesis is limited to the conceptual exploration and evaluation of alternative sensing principles for steering wheel hands-on/hands-off detection. The study concentrates on sensing concepts that may support the detection of driver interaction with the steering wheel, including contact, touch, grip, or related interaction cues. Broader driver-monitoring approaches are only considered when they directly support the steering-wheel HOD function.

The thesis does not aim to develop a production-ready HOD system. Detailed cost analysis, supplier evaluation, packaging optimization, manufacturing feasibility, certification, and compliance validation are outside the scope of the project. Feasibility is therefore discussed at a qualitative and conceptual level.

Existing automotive HOD implementations are used as contextual references and benchmarks for understanding the problem area, but they are not evaluated in detail or treated as design targets for optimization. The focus is instead placed on identifying and assessing alternative sensing directions with potential for future development.

Experimental work is also limited to proof-of-concept activities that are intended to support selected evaluation assumptions. The prototype work is not intended to provide comprehensive validation, quantitative performance benchmarking, or proof of readiness for automotive implementation.

1.6 Thesis Structure

This thesis is structured to follow the logic of the research process, moving from problem definition and contextual understanding to technology exploration, functional abstraction, concept development, evaluation, and final recommendations.

Chapter 1 introduces the background of the thesis, the industrial context of steering wheel hands-on/hands-off detection, and the motivation for exploring alternative sensing principles. The chapter also defines the purpose, research questions, scope, and delimitations of the study.

Chapter 2 presents the theoretical and industrial context of the thesis. It describes the role of hands-on/hands-off detection in advanced driver assistance and semi-autonomous driving systems, discusses the maturity of current automotive solutions, and introduces relevant sensing principles and product development concepts that support the later concept work.

Chapter 3 describes the methodology. It explains the research design and the methods used for literature study, patent analysis, cross-industry exploration, functional analysis, concept generation, concept screening, concept scoring, and exploratory prototyping. It also discusses the reliability, validity, and limitations of the method.

Chapter 4 presents the results of the development process. It reports the outcome of the technology exploration, functional analysis, requirement derivation, concept candidate development, concept combination, screening, scoring, industrial cross-check, and prototype work. The chapter shows how the initial broad set of sensing principles was gradually narrowed down into a smaller set of shortlisted concept combinations.

Chapter 5 discusses the results. It interprets the main findings, reflects on the role of functional decomposition, evaluates the methodology, discusses industrial relevance for Volvo Cars, and addresses the limitations of the study.

Chapter 6 concludes the thesis by summarizing the main outcomes, contributions, and recommended directions for future work.

2

Theoretical Background

2.1 ADAS and Levels of Driving Automation

Advanced Driver Assistance Systems (ADAS) refers to the vehicles functions that support drivers in performing parts of the driving task. Those tasks could be steering, braking, speed control, lane keeping, and hazard warning. The ADAS role depends on the level of automation and how the driving responsibility is shared between the driver and the vehicle. The SAE J3016 defines the six levels of autonomous driving. Level 0, where the driver takes full control of the driving task. At Level 1, the system either assists the steering or speed control, while the driver is still responsible for the complete control of the vehicle. At Level 2, the automated system can assist both the steering and acceleration/deceleration, but the driver is responsible to monitor the driving environment and be ready to intervene when required. At Level 3, the automated system can perform the driving task within defined conditions, but the driver must be available and ready to take the control when requested. At Level 4, the automated system can perform all driving tasks within a limited operational domain without the need of drivers intervention. At level 5, the automated system performs all the tasks related to driving under all conditions without the need of driver intervention. [6].

Level 2 automation, where the vehicle can assist with both steering and speed control, but the driver is responsible to take the control of the vehicle when it is necessary. In case of Level 3 automation, the system can perform the driving task within the defined conditions, but the driver is still responsible to take the control of the vehicle when needed. So, driver availability is still important from a safety point of view in both Level 2 and Level 3 systems.

As the automated driving functions has become more advanced so reliable Driver Monitoring Systems (DMS) has become increasingly important. The DMS may include visual attention, body posture, steering interaction, and hand contact on the steering wheel. The thesis context focuses on the Hands-On/Hands-Off detection for the steering wheel and provides an important indication of whether the driver is engaged with the steering wheel and ready to take the control of the vehicle when needed.

2.2 Steering Wheel Hands-on/Hands-off Detection (HOD)

The steering wheel HOD is a DMS function that is used to determine whether the driver is physically interacting with the steering wheel. In ADAS and in a partially automated driving system, HOD supports the vehicle is assessing whether the driver remains available to interact with the steering in case of control required in certain conditions. Hands-On/Hands-Off Detection (HOD) function has become an important function in modern automotive safety systems, particularly in Advanced Driver Assistance Systems (ADAS), Level 2 and Level 3 driver assistance and automated driving transition scenarios [5].

In such systems, the vehicle may temporarily support part of the driving task, but the driver is still expected to remain available and capable of regaining control when required. Reliable steering-wheel HOD is therefore not simply a comfort function; it contributes to supervising driver focus and helps maintain the safety logic of shared control between the vehicle and the driver [7].

From an industrial perspective, steering wheel HOD is already a mature technology and widely implemented function across other Original Equipment Manufacturers (OEMs). We observed that existing automotive solutions such as steering torque interference, capacitive sensing, or combination of multiple sensing inputs are already deployed at scale, and similar technical approaches are used across multiple OEMs. The function is therefore treated as industrialized rather than unsolved. In practice, this means that the present thesis does not assume that current solutions are fundamentally inadequate. Instead, it investigates whether alternative sensing principles may provide additional robustness or complementary information for future HOD development.

Within this context, steering wheel HOD continues to be relevant for further investigation because the range of sensing principles currently used in automotive applications appears narrower than the range of human-contact and presence-detection technologies that are used in other engineering sectors. Drivers may use different grip strengths, hand positions, different types of gloves,light contact, or environmental factors such as moisture, temperature variation, and vibration can also affect the HOD function. For this reason, it is important to understand the current HOD technology and their limitations before exploring alternative sensing solutions.

2.3 Existing Mainstream HOD Approaches

The detection of a driver's presence on the steering wheel has evolved from basic mechanical monitoring to more sophisticated electronic sensing. Historically, one typical approach was to infer driver participation from steering torque or small steering corrections measured through sensors already integrated in the steering system [8]. This approach detects indirect evidence of driver input instead of direct physical contact with the steering wheel.

The industry has also adopted capacitive sensing for steering wheel hands-on/hands-off detection. In this approach, a thin conductive sensing layer is integrated beneath the outer wrap of the steering wheel [9]. The sensor generates an electric field that is influenced by the electrical properties of the human body. When the driver's hand touches or rests on the wheel, the measured capacitance changes, allowing the system to infer hand presence [9]. Compared with torque-based inference, capacitive sensing provides a more direct and continuous indication of physical contact with the wheel.

Some recent approaches combine multiple sensing inputs rather than relying on a single principle. For example, capacitive sensing can be combined with steering torque information so that one signal may compensate for the limitations in the other under certain conditions [10]. In such a sensor-fusion arrangement, torque-based information can provide supporting evidence when capacitive detection is weakened, such as when the driver wears thick gloves.

2.4 Limitations and Challenges of Current HOD system

Although HOD are well matured and widely used, their performance can still be affected by real driving conditions. The capacitive HOD system can provide direct evidence of hand contact on the steering wheel by detecting changes in electrical field and capacitance near the steering wheel, but their sensitivity completely depends upon the interaction between driver's hand and the steering wheel surface [11]. Different conditions such as driver wearing gloves, moisture present within the interior of vehicles, contamination, and temperature variation drifts the sensing response and makes robust classification more difficult.

Other challenges are related to the driver interaction variability. Drivers may hold the steering wheel with full grip, one hand, light fingertip contact, or only temporary contact during re-gripping. The capacitive sensor may also be difficult to tune because low sensitivity can miss weak contact, while high sensitivity may detect a hand that is close to the steering wheel but in actual practice not touching it. In addition to this, metal objects may produce signals that can be misinterpreted as valid hands-on interactions.

The torque sensor has different limitations because it does not directly measure the body to steering wheel capacitance change. Instead, it detects the driver input to the steering wheel, which in simple terms is the torque. This means that even road disturbances, vibrations, and low torque driving conditions may affect the reliability of the decision [11]. An example could be that a driver may also touch the steering wheel lightly without producing a clear torque input, which leads to incorrect HOD classification.

Sensor fusion can improve the robust classification by combining different inputs such as steering torque and capacitive sensing. However, the sensor fusion also adds the system complexity because different signals must be calibrated, synchronized, and interpreted together. Therefore, the current capacitive sensing system is practical and effective, but their limitations motivates the investigation of identifying alternative sensing solutions for future development.

2.5 Cross-Industry Sensing Landscape

When it comes to different industry, the sensing technology in other industry will not be treated as irrelevant due to their end products differing from steering wheels. Instead, the important question was whether a technology addresses a related interaction problem. A sensing principle developed for human touch on a device surface, grip monitoring in a tool, presence detection in a safety system, or contact assessment in a biomedical application may still contain transferable technology.

The cross-industry sensing landscape is therefore treated in this thesis as an opportunity space. This follows the external search logic in concept generation, where literature, patents, and benchmark-related products are used to broaden the range of possible solution concepts before selection [12]. In this thesis, the logic was adapted by searching across industries for sensing principles that address comparable interaction problems. Many of these principles were not expected to be directly feasible for steering-wheel HOD and were later rejected during screening. Their value was instead to reveal a wider and more technology-diverse set of candidate principles before the evaluation process narrowed the design space.

2.6 Volvo Cars

Volvo Cars is a global automotive manufacturer whose headquarters is located in Göteborg, Sweden. Volvo Cars has been specializing in the development and production of passenger vehicles across multiple segments, including sedans, compact, mid-size Sports Utility Vehicles (SUVs). The company lays a strong emphasis on safety, electrification, and the development of Advanced Driver Assistance System (ADAS) as a part of long vision towards automated driving for future vehicles.

Within its vehicle architecture, Volvo Cars integrates a range of driver monitoring and steering based functionalities to support safe interaction of the driver with the automated systems. The steering wheel HOD is one such functionality that is integrated within the steering and uses a capacitive sensing mat to detect the presence of driver's hands on the steering wheel. The capacitive sensing method is sometimes also combined with the steering torque sensor to gain additional data in order to maintain stability.

In this thesis, Volvo Cars provide the industrial context for the steering wheel HOD problem. The ultimate objective of this thesis is not to work on modifying the existing solution but instead to explore alternative sensing concepts that could support future development within HOD area.

3

Methodology

3.1 Overall Research Approach

The overall research approach was inspired by the front-end concept development and concept selection logic presented by Ulrich, Eppinger, and Yang [12]. In particular, Exhibit 8-4 illustrates concept selection as an iterative process closely connected to concept generation, concept screening, concept scoring, and concept testing, where a broad set of alternatives is gradually narrowed toward one or more promising concepts for further development [12]. This narrowing logic was suitable for the present thesis because the project started from a broad and uncertain sensing technology space and required a structured way to reduce this space into a smaller set of concept directions.

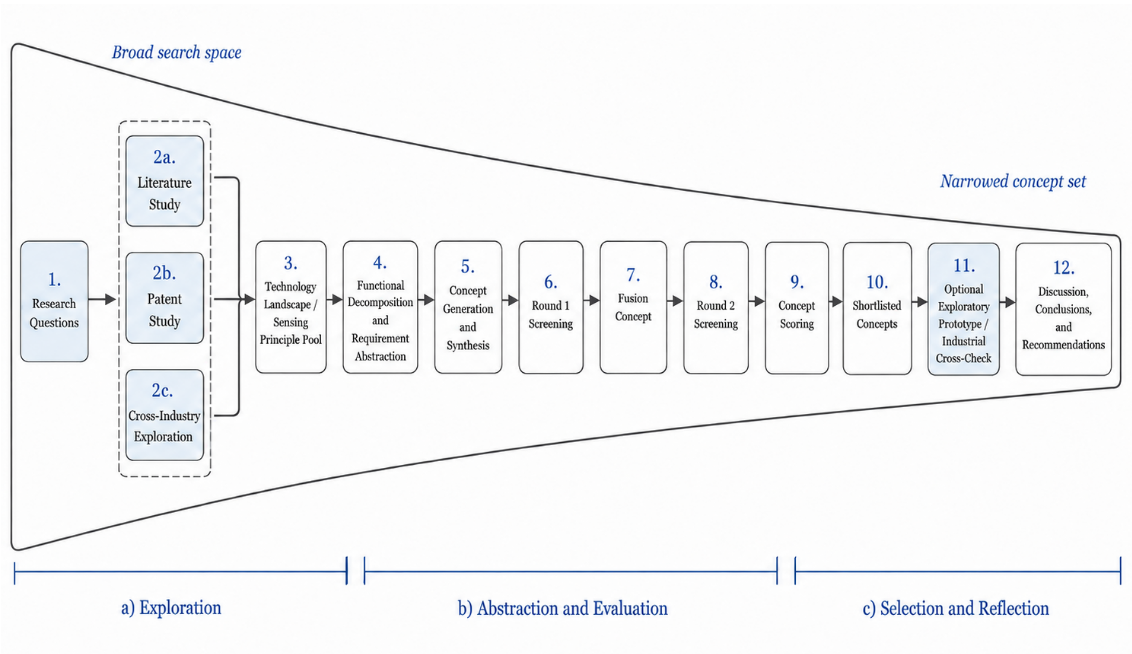


Figure 3.1: Research Design Approach for Steering Wheel Hands-on/hands-off detection (HOD)

In this thesis, the same general logic was adapted to an early-stage sensing concept exploration context. Academic literature, patents, and cross-industry technical examples were first used to expand the solution space. The identified sensing principles were then translated into steering-wheel-relevant concept candidates, assessed through functional analysis, reduced through screening, and finally compared through concept scoring. Limited prototype work and industrial feedback were used as supporting inputs.

Table 3.1 summarizes the link between the research questions, the information required to answer them, and the methods selected in this thesis.

Table 3.1: Link between research questions and methodological steps

Research question	**Methodological steps and purpose**
RQ1: Alternative sensing technologies	Literature study, patent study, and cross-industry exploration were used to identify sensing principles related to contact, grip, presence, and human interaction beyond current automotive HOD solutions.
Sub-RQ1.1: Evaluation criteria	Functional decomposition, use-case analysis, disturbance analysis, and requirement derivation were used to define evaluation criteria.
Sub-RQ1.2: Promising sensing solutions	Concept synthesis, first-round screening, and concept scoring were used to reduce and compare the candidate sensing concepts.
RQ2: Multi-sensing robustness	Concept combination, second-round screening, scoring, and industrial cross-check were used to assess sensor-fusion alternatives.
Sub-RQ2.1: Complementary sensing technologies	Fusion concept generation and scoring were used to identify combinations with complementary sensing roles and reduced single-principle limitations.

3.2 Method Selection Rationale

The methods used in this thesis were selected to match the concept-oriented research. The main task was to identify, translate, and evaluate alternative sensing principles that could be relevant for future steering wheel applications. Therefore, the methodology needed to support two activities: first, expanding the solution space beyond current automotive HOD approaches; and second, narrowing this space into a smaller set of concept candidates through a traceable evaluation process. Following the front-end concept selection logic described by Ulrich, Eppinger, and Yang [12].

Several methods were selected because they directly supported these needs. The literature study was used to identify academic knowledge on sensing principles, technical mechanisms, and reported limitations. The patent analysis was selected to complement the literature study by capturing applied technical solutions and integration logics that may not be described in scientific publications. Cross-industry exploration was used because many relevant human-contact, grip, presence, and operator-interaction solutions are found in other industrial products and applications outside the automotive domain. Functional analysis was selected to abstract the HOD problem from specific sensor technologies and to derive technology-independent requirements and evaluation criteria. Finally, concept screening and concept scoring were selected to reduce and compare the generated concept candidates in a structured way.

Other methods were considered but were not selected as primary methods. A large-scale user questionnaire was not prioritized because the main research problem concerns sensing principles and the feasibility of technical concepts rather than user preferences or acceptance. Also, the most needs and requirements are directly from Volvo. Formal semi-structured interviews were also considered, but were not used as a central data collection method because the project relied mainly on technical sources. Instead, industrial input from Volvo engineers was used as contextual feedback and cross-checking support. Full experimental testing was also not selected as a primary method because the thesis did not aim to validate a production-ready HOD system. The available time and resources were also insufficient for vehicle-level testing, environmental testing, or quantitative benchmarking against existing industrial solutions. For this reason, prototype work was limited to exploratory proof-of-concept testing intended to support selected assumptions, not to provide complete validation.

Methods such as field observation and case study research were also not suitable for the scope of this thesis. These methods would be more appropriate for investigating driver behavior and user experience. In contrast, this thesis focuses on the exploration of early-stage sensing concepts. The selected methods, therefore, emphasize technology search, functional abstraction, concept synthesis, and structured concept evaluation.

3.3 Literature Study

The literature study formed the first methodological step of this thesis. It was used to establish the problem background, summarize the current knowledge base, and justify why further study of alternative sensing principles was necessary. This follows Denscombe's view that a literature review should evaluate relevant published sources, describe the current state of knowledge, and explain why the research is needed [13, pp. 5–6].

In this thesis, the literature study had two main purposes: first, to understand how steering wheel hands-on/hands-off detection is currently addressed, and second, to identify academic knowledge on sensing principles that may be functionally transferable from other areas.

A practical challenge is that database searches can easily return thousands of papers; therefore, the literature study was designed as a search-and-filter process that balances coverage with a manageable set of candidates. This trade-off between using keywords for coverage and limiting the scope to keep results under our ability of managing them.

3.3.1 Search strategy and database

Scopus was selected as the literature tool for this literature study due to its advanced query functions, as well as its ability to export the bibliographic metadata to support transparent screening. The search process was conducted iteratively: initial queries were tested first, result sizes were then evaluated, after that, keywords and exclusions were refined to reduce the irrelevant results.

3.3.2 Organization of the search base

To avoid an unbounded generic search (e.g., "hand contact"), the literature search space was organized by sensing modality, based on the sensing hand book.[14] So that the concept candidates were collected across fundamentally different physical principles.

The modality set used in the thesis was:

- **M1** Capacitive / electric-field
- **M2** Impedance / galvanic coupling
- **M3** Mechanical force / pressure / strain
- **M4** Thermal / thermo-enabled architectures
- **M5** Optical / camera
- **M6** Ultrasonic / acoustic
- **M7** Radar / RF sensing

Query construction

For each modality, queries were constructed using four parts of terms:

1. **Target interaction**: Hand, grip, presence, hands-on/hands-off
2. **Sensing modality**: Radar, ultrasonic, camera, thermistor/heat flux, pressure/strain, capacitance/impedance
3. **Sensing category**: Detect, sensing, sensor, monitoring, tracking
4. **Context anchors**: Vehicle/automotive/cockpit/HMI/steering wheel, with cross-industry expansion when appropriate

In addition, the exclusion terms were also applied to remove those systematically irrelevant domains (e.g., rehabilitation/clinical) when they dominated the result set.

Filters and inclusion/exclusion criteria

To keep the evidence-based engineering relevant, the following filters were applied in Scopus:

- **Time window**: After 2010
- **Document type**: Journal articles and Conference papers
- **Language**: English
- **Subject areas**: Primarily engineering/physics/computer science (as applicable)

After the database filters were applied, the remaining publications were screened using two inclusion criteria. First, the publication needed to present a sensing principle that could potentially be adapted to steering wheel hands-on/hands-off detection, even if the original application was outside the automotive domain. Second, the publication needed to provide sufficient technical detail to support concept extraction, such as the sensing mechanism, system architecture, measured interaction cue, or application context.

Two exclusion criteria were then applied. Publications were excluded if their primary focus was medical diagnosis, rehabilitation, or prosthetics without a transferable sensing architecture for the steering-wheel context. Publications were also excluded when the relevant sensing modality was only mentioned as background information and was not implemented or analysed as the main method.

Concept extraction: from papers to concept cards

Each selected paper was transformed into a standardized *concept card* so that could be compared on consistent fields. Each concept card contained the following:

Must-have fields

- Concept name and modality
- Intended function (type of hands-on/hands-off evidence)
- Working principle (what physical phenomenon is measured)
- Architecture (sensor placement)
- Decision logic (how the paper infers state)
- Evidence and traceability (what is directly demonstrated; key limitations)

Optional fields

- Integration complexity (qualitative)
- Compute requirements (as reported)
- Risks and mitigation's (grounded in what the paper reports)

When a paper did not validate hands-on/hands-off directly, the concept card explicitly separated them into stage of going to be validated later. As a practical target, for each modality group, approximately 20 relevant sources were initially reviewed when sufficient search results were available. From this initial set, at least two technically relevant and transferable sources were selected for closer analysis and concept extraction where possible.

Traceability

To make sure we are not confused in the later stage of the project, as there might be so much more information at last, each concept card includes a short "primary references" list and a concise statement of what each reference contributes (e.g., hardware feasibility, signal processing method, classification logic). This will help us to trace each design claim back to published evidence in the future work.

3.4 Industrial Input and Expert Feedback

The qualitative inputs in this thesis were obtained through a discussion with internal domain experts involved in steering wheel development, driver monitoring systems, and automotive safety engineering. These interactions were not treated as formal interview data. Instead, they were used as contextual and interpretive input to support the understanding of current industrial practice and to check the relevance of the later concept evaluation.

The consulted expert group included HOD system architects, technical advisors in automotive safety systems, system design engineers, engineers directly working on the hands-on/hands-off detection implementation, and engineers from the internal perception team. These diverse roles represented a wide range of expertise ranging from sensing hardware, system-level integration, driver monitoring, and safety critical automotive functions. Rather than collecting data as formal data collection method, these inputs were served as contextual and interpretive guidance throughout the exploration and concept development process.

The primary purpose of engaging with experts was to gain a deeper understanding of current industrial practices and real world challenges related to HOD systems.

3.5 Cross-Industry Exploration

Cross-industry exploration was used to broaden the search beyond automotive hands-on/hands-off detection and to identify sensing principles from other domains where human contact, presence, grip, or interaction is detected during practical operating conditions [15]. The purpose of this step was to identify transferable sensing architectures that could inspire steering-wheel-relevant concept generation. This approach is consistent with cross-industry innovation search, in which external knowledge from other industries can be used to expand the solution space and reduce the risk of relying only on familiar or local technological trajectories [16].

Data collection was primarily carried out using targeted Google searches. This was appropriate for the cross-industry part of the thesis because many relevant solutions are not described in scientific databases but rather on company websites, product datasheets, technical manuals, application notes, and other industry-facing technical documents. The search, therefore, focused on publicly available technical material rather than peer-reviewed literature alone. Search terms were formed by combining interaction-related terms with sensing or industry terms, for example, "hands-on detection", "grip detection", "human presence sensing", and "touch sensing". When a relevant source was identified, additional searches were performed using the company name, product name, sensing principle, and application area to locate more technical information.

The selection of industries was based on the expected transfer value to the steering wheel HOD problem. Domains were prioritized when they involved human–machine interaction, safety-critical operation, harsh environmental conditions, or continuous monitoring of operator presence. Based on these considerations, the main search domains included industrial human–machine interfaces and safety controls, wearable and smart textile systems, aerospace and aviation controls, medical or rehabilitation sensing systems where the sensing principle was transferable, and selected consumer applications that involve contact or presence detection.

Each identified source was assessed. Priority was given to sources that described a clear sensing mechanism, system architecture or product-level specification. Product datasheets, patents, and application notes were considered stronger evidence than general marketing descriptions because they provided more engineering information for later stage. Sources that contained only vague claims were recorded when useful but were only treated as lower-evidence strength.

The extracted information was documented in a cross-industry search sheet. For each relevant example, the recorded information included the industry domain, source type, sensing principle, detected interaction cue, original application, possible transfer value to steering wheel HOD, and main limitations. This made the exploration traceable and allowed the identified examples to be compared with the sensing principles found in the literature and patent studies.

3.5.1 Documentation: Raw Log

All the findings in this part will be recorded in a simplified spreadsheet to maintain traceability and a clustering. Each of them captured a small set of fields that enough for following down selection concept work:

- Industry area and source type,
- What the solution detects,
- Sensing principle,
- Relevance to steering-wheel HOD,
- Key risks/unknowns,
- Evidence level,
- An initial feasibility label using a rating (Green/Yellow/Red).

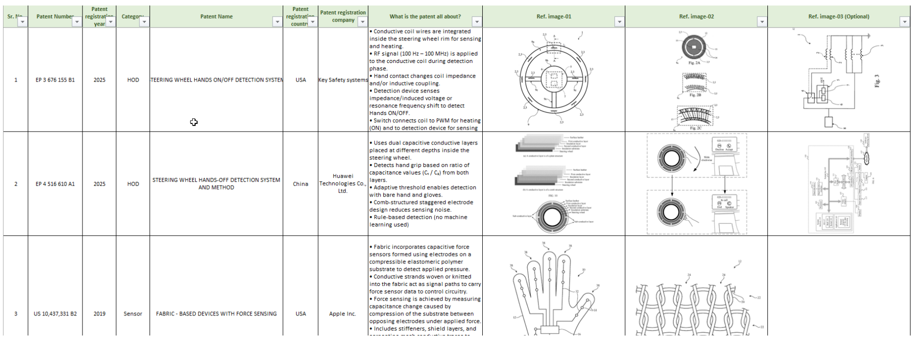
The full matrix is provided in Appendix A. After logging, those raw log were clustered into modality families. The purpose of this clustering was to move from “many individual products” to a smaller number of concept families that can be expressed as steering-wheel integration concepts.

3.6 Patent Study

A patent analysis was conducted to identify existing sensing technologies that are currently used, or could potentially be applied, for hands-on/hands-off detection and related human contact detection applications. The analysis complemented the literature review by capturing application-oriented technical solutions that are not always fully represented in scientific publications.

The patent search was carried out using Espacenet and Google Patents. A structured set of keyword-based queries was developed to explore different sensing principles that are relevant to HOD. The search covered general interaction-related queries, such as “steering wheel” AND (hands-on OR hands off OR hand-off OR grip), as well as more specific sensing approaches. These included capacitive sensing (“steering wheel” AND capacitive AND (electrode OR mutual OR self)), mechanical sensing (“steering wheel” AND (force OR pressure OR piezo OR strain)), optical sensing (“steering wheel” AND (optical OR infrared OR IR OR camera OR ToF)), and acoustic-based approaches (“steering wheel” AND (ultrasonic OR acoustic)*). In addition, broader human-interface contexts were explored using queries such as (handle OR joystick OR yoke) AND “grip detection” AND (capacitive OR force OR optical).

Through this process, the patent analysis helped to build a clearer picture of the existing technology landscape. It delivered insights into relevant sensing principles, practical system-level approaches, and broader innovation trends across both automotive and other related domains.



Sr. No	Patent Number	Patent registration year	Category	Patent Name	Patent registration country	Patent registration company	What is the patent all about?	Ref. image-01	Ref. image-02	Ref. image-03 (Optional)
1	EP 3 676 155 B1	2025	HOD	TEERING WHEEL HANDS ON/OFF DETECTION SYSTEM	USA	Key Safety systems	• Conductive coil wires are integrated inside the steering wheel rim for sensing and heating. • RF signal (100 Hz – 100 MHz) is applied to the conductive coil during detection phase. • Hand contact changes coil impedance and/or inductive coupling. • Detection device senses impedance/induced voltage or resonance frequency shift to detect Hands ON/OFF. • Switch connects coil to PWM for heating (ON) and to detection device for sensing			
2	EP 4 516 610 A1	2025	HOD	STEERING WHEEL HANDS-OFF DETECTION SYSTEM AND METHOD	China	Huawei Technologies Co., Ltd.	• Uses dual capacitive conductive layers placed at different depths inside the steering wheel. • Detects hand grip based on ratio of capacitance values (C_1 / C_2) from both layers. • Adaptive threshold enables detection with bare hand and gloves. • Comb-structured staggered electrode design reduces sensing noise. • Rule-based detection (no machine learning used)			
3	US 10,437,331 B2	2019	Sensor	FABRIC - BASED DEVICES WITH FORCE SENSING	USA	Apple Inc.	• Fabric incorporates capacitive force sensors formed using electrodes on a compressible elastomeric polymer substrate to detect applied pressure. • Conductive strands woven or knitted into the fabric act as signal paths to carry force sensor data to control circuitry. • Force sensing is achieved by measuring capacitance change caused by compression of the substrate between opposing electrodes under applied force. • Includes stiffeners, shield layers, and			

Figure 3.2: Example of Patent Analysis Matrix

3.7 Sensing Principle Synthesis and Concept Candidate Development

The purpose of this stage was to transform the broad set of sensing inputs identified in the previous methodological steps into steering-wheel-relevant concept candidates suitable for later screening and evaluation.

During the industry and academic study, we produced a large set of raw sensing principles, but these principles did not directly correspond to steering-wheel concepts. Many of the identified sources described technologies in other contexts and therefore could not be evaluated one-to-one as candidate concepts for steering-wheel HOD. Instead, a synthesis step was developed to reinterpret these principles into the thesis context.

The synthesis process relied on three input streams. Academic literature provided information on sensing principles, working mechanisms, signal types, and reported sensing capabilities. Patents provided examples of technical solution logic, especially where a sensing principle was integrated into a steering wheel or vehicle-related interface. Cross-industry references provided mature or semi-mature examples from other application areas where similar interaction-detection functions were addressed.

3.7.1 From Sensing candidate principles to Sensing concepts

Because the collected raw material came from different source types and different application domains, the first synthesis task was to cluster the identified principles into higher-level groups. This was done using the underlying sensing physics as the primary grouping logic. In practice, a principle described in a paper, a patent, and a product example could still belong to the same family if the fundamental sensing mechanism was the same.

At this stage, the raw principles were then grouped into concept families. These families were still not final concepts. Instead, they were seen as an intermediate structure that would help to organize the design space and make the overlap visible across the literature, patents, and cross-industry examples.

3.7.2 Concept synthesis table

To manage the large number of source items and maintain traceability during synthesis, a master concept synthesis table was created. Each entry recorded the source identity, source type, original application example, sensing principle, detected variable, key strengths, key limitations, and a steering-wheel translation.

Raw Source I	Source Typ	Industry	Original Example	Sensing Principle	Detected Variable	Key Strength	Key Limitation	Steering Wheel Translation	Concept Family	ML/I	Comments
P-01	Patent	Automotive	Roof-mounted infrared camera system monitoring whether driver hands are on the	Infrared camera + image recognition / CNN-based hand detection	Driver hand presence on steering wheel; hands-on / hands-off state	No modification to steering wheel structure; suitable for existing vehicle platforms; non-contact sensing; claimed low cost and good adaptability	Depends on line of sight, image quality, lighting/occlusion conditions, and model robustness; contact is inferred visually rather than directly measured	Roof-mounted or cabin-mounted IR camera observing steering wheel region to classify hands-on/off	M5 — Optical / Vision-based	ML/DL	C5 Merged
P-02	Patent	Automotive	Driver monitoring system inferring hand-wheel interaction from image sensor, body	Vision-based driver monitoring with keypoint extraction and driver model; hand-wheel state	Hands-on / hands-off condition, with force/contact state inferred from body pose, hand vicinity,	Rich contextual information; can use existing cabin sensing and driver monitoring inputs; no steering wheel hardware integration required	Indirect inference rather than direct physical touch sensing; high algorithmic complexity; sensitive to occlusion, pose estimation quality, and system calibration	Cabin camera or image sensor estimating hand-wheel interaction from driver pose and contextual signals	M5 — Optical / Vision-based		C5 Merged
P-03	Patent	Automotive	Hands-on/off detection based on steering variables such as torque, evaluated with	Machine-learning estimation from steering-related signals, especially steering torque /	Hands-on / hands-off state estimated from steering torque or other steering variables	Does not require capacitive sensor or camera; avoids extra wheel-mounted touch hardware; potentially easier packaging in existing steering system	Detection is indirect; likely sensitive to driver behavior, road conditions, and steering context; may struggle with weak hand input or ambiguous torque patterns	Hands-on/off estimation from steering torque / steering variables using ML, potentially as a software-based or steering-system-based concept	M3 — Mechanical force / Pressure / Strain		C9 Merged
P-04	Patent	Automotive	Optical-effect touchpad integrated into a steering wheel for touch and hand interaction detection	Embedded optical sensing using a light source, optical waveguide / deformable optical	Hand/finger touch position, pressing direction, gesture-like movement, and contact on steering	Embedded in steering wheel; potentially rich spatial interaction data; can detect touch behavior without relying on electric-field sensing	Mechanically and optically complex; integration and durability risk; likely sensitive to packaging, contamination, and calibration	Embedded optical touch/grip sensing zones integrated into steering wheel rim or spoke, using light propagation/deformation	M5 — Optical / Vision-based		
P-05	Patent	Flexible sensors	Piezoresistive foam-based flexible pressure sensor for curved or bendable surfaces, with	Piezoresistive foam layer whose resistance changes under applied pressure, combined	Applied pressure / touch pressure distribution	Large-area flexible sensing potential; direct pressure-related signal; suitable for soft/curved surfaces; patent explicitly shows steering wheel applicability	Measures pressure rather than pure hand presence; possible drift, hysteresis, durability, and material aging concerns; requires layered integration under surface	Pressure-sensitive layer under steering wheel cover for grip/contact detection across wheel surface or grip zones	M3 — Mechanical force / Pressure / Strain		C2 Merged
R-001	Product	Industrial HMI	Projected capacitive proximity/touch sensing for industrial interfaces	Capacitive / electric-field sensing	Touch + proximity	Mature and proven; directly relevant to hands-on/off style detection; supports non-mechanical sensing	Sensitive to water films, EMC, and shielding/calibration requirements	Distributed capacitive electrodes under steering wheel cover for touch/proximity-based hands-on detection	M1 — Electric-field / Capacitive		C1 Kept as candidate evidence
R-002	Product	Industrial HMI	Resistive and IR touchscreen approaches for gloved-hand industrial operation	Resistive / pressure-based touch sensing	Touch, possibly force-related contact	Glove-compatible; less moisture-sensitive than capacitive; useful as non-capacitive contact logic	Usually designed for planar touch interfaces; limited multi-touch capability; signal depends on force distribution	Pressure-sensitive grip zones or under-cover pressure layer for glove-tolerant hand-contact detection	M3 — Mechanical force / Pressure / Strain		C2 Merged
R-003	Product	Industrial safety switches	Inductive safety switch for position monitoring of	Inductive proximity sensing	Presence/position of metal target	Robust and proven in safety architecture; useful as benchmark for safety-oriented sensing logic	Detects metal targets rather than human hand contact; poor transferability to soft steering wheel	Not a primary steering wheel HOD concept; mainly a reference for safety-oriented	M7 — Radar / mmWave		Reference / fusion

Figure 3.3: Example of Concept Synthesis Table

The full table is provided in Appendix A. This table served as a bridge between the exploration stage and the later concept selection stage.

3.7.3 Concept Merging

Once the raw principles had been organized in the table, the next step was to identify the concept seeds and determine whether they should remain separate or be merged. In this thesis, a concept seed referred to an early steering-wheel-relevant interpretation of a sensing principle, usually still supported by multiple sources. The important methodological point was that a source item was not automatically treated as one concept. Instead, several source items were merged when they implied essentially the same steering-wheel concept architecture.

This merging was guided by three questions:

- Do the source items rely on the same core sensing mechanism?
- Would they lead to the same or very similar steering-wheel concept sketch?
- Would they face broadly similar integration conditions, risks, and limitations in the steering-wheel context?

If the answer to these questions was largely yes, the items were merged into one concept candidate. For example, different pressure-related principles were merged when they all converged to a similar steering-wheel architecture, such as a pressure-sensitive under-cover sensing layer. Likewise, several external observation concepts were merged when they all corresponded to a cabin-mounted vision-based interpretation of driver interaction. In contrast, concepts were kept separate when they shared only a broad family label but implied substantially different steering-wheel architectures, such as external vision-based observation versus embedded optical sensing inside the wheel rim.

However, some principles were excluded from standalone concept status because they were considered too weakly transferable or insufficiently distinct. In several cases, a principle was be logged as reference-only inspiration rather than an independent candidate. This happened when the original source helped broaden the search, but did not provide a sufficiently applicable steering-wheel direction on its own.

3.8 Functional Analysis and Requirement Derivation

In order to evaluate sensing concepts, the Hands-On/Hands-Off Detection (HOD) problem was formulated as a black-box function. The black-box representation defines the system boundary and specifies the functional transformation from inputs to outputs under relevant disturbances [12].

Since the project aimed to explore sensing principles beyond existing steering-wheel HOD solutions, it was necessary to describe the detection problem in a technology-independent way before evaluating specific concepts. Functional analysis was therefore used to clarify what the HOD function must achieve, rather than how it should be implemented.

The analysis started from a black-box definition of the HOD function, then followed by a decomposition of the detection problem into sub-functions to define the expected operating envelope of the system.

The purpose of this method was to derive requirements in a traceable manner. Instead of defining evaluation criteria directly from individual sensor technologies, the requirements were derived from the functional needs and operating conditions of the HOD problem. These requirements were then used as the basis for the criteria applied later in concept screening and concept scoring. In this way, the evaluation framework was expected to remain consistent across different sensing principles and suitable for comparing both single-sensor concepts and multi-sensing combinations.

The expected output of the functional analysis was therefore as a structured set of technology-neutral requirements and evaluation criteria. These outputs provided the link between the problem definition and the subsequent concept selection activities.

3.9 Concept Screening

Following concept generation and synthesis, the next methodological step was concept screening. The purpose of this stage was to reduce a relatively broad concept space into a smaller and more manageable set of candidates that could be compared in a structured way later. Concept screening was as an initial reduction step intended to remove sensing principles that were clearly incompatible with the hands-on/hands-off detection function or with basic steering-wheel use conditions, before more detailed concept evaluation was carried out.

This approach was also aligned with the concept selection method described by Ulrich, who recommend a two-stage process consisting of concept screening and concept scoring. In their framework, concept screening is intended to provide a coarse comparison that narrows the range of alternatives, while more detailed scoring is reserved for the concepts that remain after this first reduction [12].

The present thesis adopted this general logic, but the actual screening process developed into two consecutive screening rounds rather than one. This was because the project direction evolved during the work: after the first reduction of individual sensing concepts, the focus then shifted from identifying promising single sensing principles toward exploring combined multi-sensing solutions based on sensor fusion.

3.9.1 First Screening Round: Screening of Individual Concepts

In the first screening round, the candidate concepts developed from the synthesis stage were screened as individual sensing concepts. At this point, each concept represented a distinct steering-wheel-relevant sensing architecture. The intention of the first screening round was to narrow the set of single-concept candidates to those that appeared sufficiently relevant, transferable, and conceptually meaningful for steering-wheel HOD.

The screening was conducted using a Pugh-style comparison matrix with the distributed capacitive sensing layer concept used as the reference concept [12]. Each alternative concept was assessed against the reference by using the relative ratings "+", "0", and "-". The screening criteria were selected to reflect the needs of steering-wheel hands-on/hands-off detection at concept level. The criteria were:

- Functional relevance to HOD
- Output stability and Decision support
- Robustness to user and Environmental variation
- Integration and Transfer feasibility
- Evidence maturity and Credibility
- Development and Validation burden
- Fusion complementarity potential

At this stage, the matrix was used as an early filtering tool. The intention was to identify concepts with sufficient functional value and fusion potential, while excluding concepts that were less suitable for continued development within the steering-wheel context.

3.9.2 Transition from Single Concepts to Sensor Fusion

During the concept selection process, the project direction developed further from comparing individual sensing principles toward exploring multi-sensing combinations. This shift was motivated by the observation that several single concepts appeared to have complementary strengths and weaknesses rather than one concept clearly dominating across all dimensions [17]. Some concepts provided more direct contact-related evidence, while others offered non-contact, or system-level support. As a result, a sensor-fusion direction became more relevant than selecting one single sensing principle in isolation.

3.9.3 Second Screening Round: Screening of Fusion Concepts

Once the sensor-fusion direction had been adopted, the shortlisted single concepts were recombined into three-way concept sets. This then produced a new concept space consisting of fused sensing architectures. Because this new combination space again became too large for direct detailed evaluation, a second screening round was introduced.

The role of this second screening round was similar to the first: to reduce the new concept space before moving to more detailed evaluation. However, the object of screening was now different. Instead of asking whether one individual sensing principle was meaningful in isolation, the second screening round considered whether a combination of sensing concepts feasible fusion architecture.

This second screening round remained consistent with the overall concept selection methodology. The concept selection framework is not restricted to one fixed level of detail, and Ulrich also explicitly note that concept selection can be used repeatedly throughout the development process and at different levels of abstraction [12]. The second screening round in this thesis should therefore be understood as a repeated application of the same concept selection logic, but now at the fusion-concept.

3.9.4 Role of Screening Relative to Later Concept Evaluation

Although both screening rounds involved structured comparison, they were still intended to remain reduction steps. The purpose was to narrow the range of concepts under consideration, not to establish the final ranking with fine precision.

For this reason, the present section does not elaborate the detailed scoring process. Instead, it documents how the concept space was reduced through two screening rounds: first by screening individual sensing concepts, and second by screening combined fusion concepts. The more detailed weighting, rating, and ranking logic belongs to the subsequent concept evaluation section.

3.10 Concept Scoring

After concept screening, the remaining concepts were evaluated through concept scoring. The purpose of this stage was to compare the shortlisted concepts in a more differentiated way than in the screening step.

This also follows the concept selection logic described by Ulrich, in which concept scoring is used for a more detailed comparison of the remaining concepts. In this framework, concept scoring introduces weighted criteria and a finer rating scale in order to make trade-offs between alternatives more explicit [12].

3.10.1 Basis for the Scoring Criteria

The scoring criteria were derived from the earlier functional decomposition, requirement abstraction, and concept screening work. In particular, the project planning report had already identified several technology-independent dimensions that the concepts should be judged against, including the type of interaction detected, stability of the output, tolerance to user and environmental variation, and conceptual applicability in the steering-wheel context.

During the project, these detailed requirements were first developed as a broader evaluation pool. For concept scoring, they were then consolidated into a smaller number of higher-level criteria. This was done in order to keep the scoring matrix consistent with the concept selection method from Product Design and Development, while still maintaining traceability to the earlier requirement analysis.[12] The detailed criteria were therefore retained as supporting sub criteria, where the scoring itself was carried out at a higher level.

Each combination was rated against seven evaluation criteria derived from the requirement framework established in the result chapter. The scoring criteria and weights were:

- Detection performance (25%)
- Robustness to disturbances (20%)
- Dynamic decision quality (15%)
- Fusion complementarity and redundancy benefit (15%)
- Engineering integration feasibility (15%)
- System complexity and resource burden (7%)
- Industrialization feasibility (3%)

The combinations were rated on a five-point scale, and weighted scores were calculated to obtain the total score for each fusion concept.

3.11 Proof-of-Concept Method

To support concept exploration and evaluation, a Proof of Concept (PoC) was developed. The primary purpose of PoC is to provide an initial understanding of the behaviour of the selected sensing principle in controlled conditions. The selected concept is based on Swept Frequency Capacitive Sensing (SFCS) and is described in the following subsections.

The PoC activity only focused on assessing the feasibility of detecting a variety of interaction conditions, including variations in the presence and intensity of the contact, such as light/hard touch, firm contact, pinch, hard press, hand detection through gloves and non-contact scenarios within the sensing region.

At this stage, the PoC work was exploratory work and was not intended to provide quantitative performance validation. Instead, it was used to verify the working of the setup and the signal behaviour that can be produced. The PoC design and testing approach are described in the following subsections.

3.11.1 Proof-of-Concept setup

A simplified Proof-of-Concept of the C7 (Conductive Foam Grip Sensing) was developed to demonstrate the sensing behaviour. As mentioned above, the PoC is based on the Swept Frequency Capacitive Sensing (SFCS) principle, which has already been explored by many researchers to detect sensing interactions across different applications.

The conventional capacitive sensing principle operates on a single excitation of frequency. In comparison, SFCS is a sensing technique that measures changes in electrical properties across a range of frequencies thereby resulting in a frequency dependent impedance profile [18]. The range of frequency points provides a significantly richer information as it capture multiple data points which describes the interaction between the human body and sensing element [19]. The advantage of SFCS is that it performs a frequency sweep and captures the resulting impedance response of the system. This approach has the potential to detect more complex interactions and distinguish between touch, grip, and deformation due to external objects. The steering wheel is the primary interaction for the driver and the foam is just beneath the artificial leather covering, which provides better comfort and grip. Previous studies has shown that the conductive foam enables the detection of multiple interaction modes, including touching, compressing, pinching, and grasping [20]. By analyzing different interactions, the system is expected to provide richer information as compared to traditional single frequency capacitive sensing.

3.11.2 Test logic

The PoC was tested for its functioning and sensitiveness. The software used for this PoC was Arduino IDE and the variation in response was continuously observed on the Arduino IDE serial plotter. Different objects interactions with the sensing tip was carried out to detect the varying amplitude. The section 4.10 shows couple of test that were carried out.

3.12 Reliability, Validity, and Limitations of the Method

This thesis is an exploratory concept-development study. The purpose was to explore, structure, and compare alternative sensing principles for steering-wheel hands-on/hands-off detection, not to prove the final technical feasibility of one solution through full-scale testing. The project planning report therefore defined the work as a conceptual and forward-looking study, with production-ready development, detailed cost analysis, large-scale manufacturing feasibility, certification, and full experimental benchmarking kept out of scope. Any feasibility discussion was restricted to a qualitative and conceptual level.

3.12.1 Reliability of the Method

In the context of this thesis, reliability should not be understood in the narrow sense of repeated measurement. The concept generation, screening, and scoring stages were partly qualitative and judgement-based. This is consistent with Denscombe's discussion that qualitative research often depends more strongly on researcher interpretation and therefore requires transparency in procedure rather than strict instrument repeatability. Denscombe uses the term dependability for this issue and argues that it is addressed mainly through transparency in how the research is conducted [13].

The reliability of the present method was supported in three ways. First, the project followed a documented sequence: cross-industry and academic exploration, functional decomposition, requirement abstraction, concept generation and synthesis, concept screening, concept scoring, and reflection. This reduced the risk of ad hoc decisions and created a traceable link between early exploration and later evaluation. The planning report had already defined this as the intended method structure.

Second, the evaluation did not rely on intuition alone. The identified sensing principles were compared through structured matrices in both screening and scoring. This follows the concept selection method in *Product Design and Development*, where concept screening and concept scoring are used as formal comparison steps and where the process is intended to create a record of decision making rather than only an informal preference ranking [12].

Third, the process included repeated reflection and revision. Concept clustering, merging, exclusion, screening, fusion generation, and later scoring were all reviewed when new understanding emerged. This iterative character reduces the risk that early assumptions remain unchallenged.

At the same time, the reliability of the results is limited by the fact that several ratings were based on engineering judgement rather than measured prototype data. If another team repeated the same study, it is likely that the overall concept structure would be similar, but some detailed ratings, weightings, or inclusion/exclusion decisions might differ. This is an expected limitation in early-stage concept evaluation.

3.12.2 Validity of the Method

In this thesis, validity refers to whether the method was appropriate for evaluating what it claimed to evaluate: the potential of alternative sensing principles for steering-wheel HOD at an early concept level. This required alignment between the research objective, the functional decomposition, the evaluation criteria, and the screening and scoring process.

Since the work was qualitative and exploratory rather than experimentally validated, validity was discussed through the concepts of credibility and transferability. This follows Denscombe's discussion of trustworthiness in qualitative research, where credibility relates to whether the findings are convincing in relation to the available evidence, and transferability relates to whether the reasoning can be meaningfully applied in another setting [13, pp. 349–351].

The validity of the method was supported by the structure of the research design. The concept evaluation did not begin directly from available technologies. Instead, the detection problem was first abstracted into a technology-independent functional description and a set of evaluation criteria.

A second source of validity was the use of multiple evidence sources. The concepts were not generated from a single literature stream, but from academic papers, patents, and cross-industry technical examples. The triangulation across contrasting data sources can be one way of strengthening confidence that findings are "on the right lines." In this thesis, the use of multiple source types reduced the risk that the concept space would reflect only one narrow domain or one type of publication.

A third source of validity was traceability. The use of a master concept synthesis table and later reduction tables made it possible to document how raw sensing principles were clustered, merged, retained, or excluded. This was important because the project did not evaluate raw source items directly. Instead, it evaluated synthesized concept candidates. By keeping the transformation from source material to concept candidate explicit, the risk of arbitrary concept construction was reduced.

However, the validity of the method is also limited in several ways. Most importantly, the thesis did not validate the concepts experimentally. Therefore, the scoring results should be interpreted as concept-level judgements about expected potential, not as proof of actual system performance. In addition, some of the source material came from other industries or research domains. Even though transferability was considered explicitly, the steering-wheel translations still involved interpretation.

3.12.3 Limitations of the Method

Several limitations follow directly from the chosen research design.

First, the concept evaluation was partly judgement-based. Although the use of structured matrices improved consistency, the ratings still depended on engineering interpretation of qualitative evidence, patents, literature descriptions, and conceptual applicability. This means that the outputs are not independent of the researchers' reasoning. To mitigate this limitation, the ratings were documented through explicit criteria and rationale, and the scoring results were interpreted as comparative decision support.

Second, many evaluations were qualitative because prototype data were not available. The project planning report had already delimited the work to conceptual exploration and evaluation, with only optional proof-of-concept activities if time and resources allowed. As a result, important questions such as signal quality, false positive rate, environmental robustness, and detailed packaging could not be tested directly for most concepts.

Third, industrial feasibility was treated only at a conceptual level. The project explicitly deprioritized large-scale manufacturing feasibility, certification, supplier readiness, and full cost optimization as primary decision drivers. This was appropriate for the exploratory purpose of the thesis, but it also means that a concept scoring highly in this study should not be interpreted as ready for industrial implementation.

Fourth, the ranking results were influenced by the choice of criteria and weights. Since concept scoring uses weighted criteria, different reasonable weighting choices could change the relative ranking of some concepts. To reduce the risk of over-interpreting the numerical scores, the final ranking was examined together with the score differences between alternatives. Small differences in total score were treated cautiously, while larger gaps and recurring high performance across several criteria were considered more meaningful. The scoring outcome was therefore used to identify a shortlist of promising directions.

Fifth, the project moved through several levels of abstraction: raw sensing principles, single concepts, and later fusion concepts. This was necessary for the research purpose, but each transition introduced interpretation. The final shortlisted concepts were therefore not direct representations of any single source, but rather concept candidates derived from synthesis and reduction.

4

Development Result

4.1 Technology Exploration Results

The technology exploration resulted in a set of sensing principles that were relevant for steering wheel hands-on/hands-off detection. To enable a structured comparison across a wide range of technologies, the identified solutions were then classified based on their underlying physical sensing principles.

4.1.1 Literature Study Result

The literature study resulted in a set of selected papers that were used as inputs for concept generation.

The selected papers were organized according to the sensing modalities defined in the methodology: capacitive/electric-field sensing, impedance-based sensing, mechanical force/pressure/strain sensing, thermal or thermo-enabled sensing, optical/camera-based sensing, ultrasonic/acoustic sensing, and radar/RF sensing. For each modality, the initial search results were screened through title, abstract, and full-text review. For example, capacitive/electric-field sensing was represented by studies on touch and proximity detection [21]; mechanical interaction sensing was represented by studies on pressure mats, tactile skins, and strain-sensitive materials [22]; and non-contact sensing was represented by camera-, ultrasonic-, and radar-based approaches [17, 23]. Around twenty papers per modality were examined in more detail where sufficient relevant literature was available.

Citation count was used as a prioritization criterion when multiple papers were technically relevant. However, citation count alone was not used as an automatic selection rule. A highly cited paper was only retained if its sensing principle, system architecture, or decision logic could reasonably support concept generation for steering-wheel hands-on/off detection. Papers that were influential in their original field but not transferable to the steering-wheel context were excluded.

The final number of selected papers differed between modalities. This was because some sensing areas contained many transferable studies, while others contained only a small number of papers that matched the thesis scope. Therefore, the final literature set reflects both academic relevance and transferability to the specific design problem.

Table 4.1: Final selected literature by sensing modality

Modality	**Sensing focus**	**Selected papers**
M1	Capacitive / electric-field	8
M2	Impedance / human touch identification	1
M3	Mechanical force / pressure / strain	4
M4	Thermal / thermo-enabled skin	2
M5	Optical / camera-based	4
M6	Ultrasonic / acoustic	3
M7	Radar / RF sensing	2

The full list of selected papers is provided in Appendix B.

4.1.2 Patent Study Result

The patent study was conducted as an additional external search to support concept generation. Since the main purpose of the thesis is exploratory concept development rather than intellectual property analysis, the patent study was kept at a limited scope. For each patent-search direction, only the first 20 results were reviewed, ordered either by relevance or by recency. The aim was to identify representative sensing architectures and implementation patterns that could contribute to steering wheel hands-on/off detection, rather than to perform a complete patent landscape or freedom-to-operate analysis.

The search resulted in five selected patents that were considered relevant for concept generation. These patents were selected because they either directly addressed steering wheel hands-on/off detection or described a sensing structure that could be conceptually transferred to a steering wheel context. The selected patents covered four main technical directions: camera-based hand detection, steering-system signal inference, optical touch sensing, and pressure-sensitive material sensing.

The first identified direction was camera-based hands-on/off detection. One selected patent used an infrared camera and image processing to identify whether the driver's hands are on or off the steering wheel. This direction represents a non-contact approach, where the steering wheel does not need to be modified with embedded sensing layers. Its main contribution to concept generation was the idea that hands-on/off status can be detected from the cabin environment rather than from the steering wheel rim itself. However, this approach also introduced potential concerns related to camera placement, occlusion, lighting conditions, and privacy.

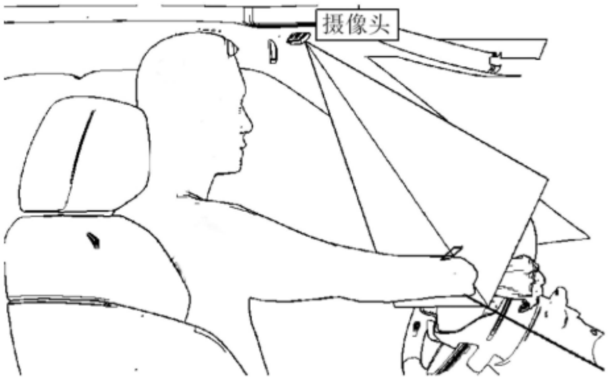


Figure 4.1: Example of Camera-based Patent[1]

The second direction was steering-system signal inference. Two selected patents were related to estimating hands-on/off status indirectly from steering torque, steering response, driver dynamics, or vehicle signals. These patents showed that hands-on/off detection does not necessarily require direct contact sensing. Instead, the driver's interaction with the steering system can be inferred through torque patterns, applied force estimation, or machine-learning-based interpretation of steering signals. This direction was relevant because it suggested a low-hardware or sensorless approach. At the same time, it was considered uncertain in cases where the driver lightly rests the hands on the wheel without applying significant torque.

FIG. 5

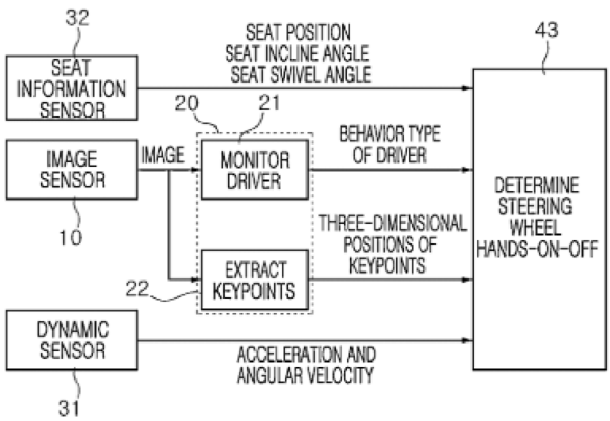


Figure 4.2: Example of Steering System Signal Based Patent[2]

The third direction was optical touch sensing integrated into the steering wheel. One selected patent described an optical-effect touchpad concept, where mechanical deformation caused by touch or pressure is detected through an internal optical structure. This patent was relevant because it suggested an alternative to capacitive touch sensing. Instead of relying on the electrical coupling between the human body and the sensor, the concept detects physical interaction through deformation and optical response. This could potentially provide advantages under conditions where capacitive sensing is less reliable, such as gloves or surface contamination. However, the approach may involve higher integration complexity due to packaging, durability, and optical stability requirements.

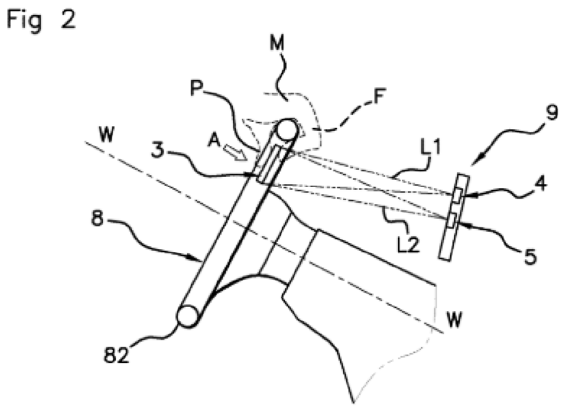


Figure 4.3: Example of Optical Integrated Patent[3]

The fourth direction was pressure-sensitive material sensing. One selected patent described a piezoresistive foam-based pressure sensing structure with an electrode array and soft cover layer. Although this patent was not specifically developed for steering wheel HOD, it was considered transferable because the material structure could potentially be integrated into the steering wheel rim as a soft pressure-sensitive layer. This direction was relevant because it directly measures grip pressure or contact distribution, which is closely related to the functional requirement of detecting whether the driver is holding the steering wheel. The main uncertainties are related to long-term durability, material ageing, drift, and integration into automotive trim.

Overall, the patent study confirmed that hands-on/off detection can be approached through both direct and indirect sensing strategies. Direct strategies include pressure-sensitive materials and optical touch structures integrated into the steering wheel. Indirect strategies include camera-based observation and steering-system signal inference. The patent study also showed that several concepts could provide complementary information: for example, pressure sensing can provide direct grip evidence, while steering torque or camera-based methods can provide system-level or contextual information. Therefore, the patent study supported the later decision to consider sensor-fusion concepts rather than relying only on a single sensing principle.

The selected patents were converted into patent-based concept cards and included in the broader concept generation pool. These patent-derived concepts were not treated as final design solutions. Instead, they were used as structured inputs for

Table 4.2: Summary of selected patents from the patent study

Patent	Technical direction	Main sensing logic	Contribution to concept generation
CN 211107382 U[1]	Camera-based detection	Infrared camera and image processing to classify the driver's hands are on or off the steering wheel.	Introduced a non-contact HOD concept without modifying the steering wheel rim.
US 12365358 B2[2]	Driver force estimation	Driver and vehicle signals are used to estimate the force applied to the steering wheel.	Introduced an indirect, model-based interpretation of driver-wheel interaction.
DE 102024-200088 B3[24]	Steering torque machine learning	Steering quantities are interpreted by a trained model.	Introduced steering-system signal inference and active/domain-aware HOD logic.
US 11110799 B2[3]	Optical touch sensing	Touch mechanical deformation is detected through an optical-effect touchpad structure.	Introduced an alternative direct touch sensing principle that does not rely on capacitive.
US 202302-28633 A1[25]	Piezoresistive foam pressure sensing	A pressure-sensitive foam layer and electrode array are used for pressure or contact mapping.	Introduced a transferable soft pressure-sensing layer for potential steering wheel grip detection.

subsequent concept screening and concept combination. Their main contribution was to provide practical examples of sensing architectures, possible integration patterns, and technical risks that could be considered when adapting alternative sensing principles to steering wheel hands-on/off detection.

4.1.3 Cross-Industry Study Result

The cross-industry exploration generated a set of transferable sensing principles and product analogies from industries outside the conventional automotive hands-on/off detection domain. The search covered industrial human–machine interfaces, wearables and smart textiles, aerospace-related safety controls, optical touch systems, radar-based presence sensing, and structural measurement technologies. The results showed that several non-automotive domains address similar sub-problems.

The findings were first recorded as raw entries and then clustered into modality families. Each entry was assessed according to its sensing principle, detected variable, possible transfer to a steering wheel environment, and main integration risks.

Industrial HMI and Safety Controls

The industrial HMI search showed that many operator interfaces rely on capacitive or proximity-capacitive sensing, even when designed for gloves, contamination, sealed surfaces, and harsh environments. It confirmed that capacitive sensing remains a dominant solution family in robust touch interfaces outside the automotive domain. However, since capacitive sensing is already widely used in current steering wheel HOD systems, these findings were not treated as a fundamentally new sensing modality.

Instead, the main transferable value from industrial HMI was found in the implementation strategies used to improve robustness. These include sensing through protective overlays, filtering for wet or contaminated conditions, compensation for baseline drift, and attention to EMC/EMI robustness. Therefore, industrial HMI did not mainly contribute a new principle, but it supported the formulation of an improved capacitive/electric-field concept with stronger robustness considerations.

A smaller number of industrial touch technologies based on resistive or pressure-sensitive principles were also identified. These were considered more transferable as non-capacitive sensing alternatives, because they detect applied force rather than electrical. This result led to the inclusion of force-sensitive resistor and pressure-film-based sensing as a relevant modality family for further concept development.

Wearables, Smart Textiles, and Flexible Force Sensing

The wearables and smart textiles search produced one of the most relevant non-capacitive modality families. Several flexible sensing principles were identified, including force sensing resistors, piezoresistive films, conductive rubber, textile-based pressure sensors, and flexible strain sensors. These technologies are commonly used to detect pressure, deformation, or grip-related force in soft or wearable systems.

The main transfer opportunity was the possibility of embedding thin force or pressure sensing elements beneath the steering wheel trim. Compared with capacitive sensing, force-based sensing has a clear potential advantage in glove and moisture robustness, because it does not rely on direct electrical coupling with the skin. It can also support grip-intensity detection rather than simple touch/no-touch classification.

However, the study also identified several risks. The force applied by the hand would be distributed through leather, foam, and other trim materials before reaching the sensor. Therefore, the effective pressure at the sensor may vary depending on grip position, hand size, trim stiffness, and long-term material aging. FSR-based concepts also introduce concerns regarding drift, creep, temperature sensitivity, and repeatability over the vehicle lifetime. As a result, force-based sensing was considered promising, but it would require careful mechanical stack-up design, segmentation, calibration, and durability testing.

Structural Strain-Based Sensing

Structural measurement technologies, especially strain gauges, were also investigated. Strain gauges are widely used in force, torque, load, and deformation measurement, and therefore provide a possible indirect method for detecting driver interaction with the steering wheel. The principle could be transferred to HOD by measuring deformation of the wheel rim, spokes, or internal frame caused by grip force or steering input.

The study showed that a single strain gauge would not be sufficient for full steering wheel coverage, because strain gauges are local measurement devices. For HOD, the relevant concept would instead require a multi-point strain sensing network placed at structurally meaningful locations, such as spokes or internal rim support points. Such a system could classify grip presence or load patterns based on distributed structural deformation.

The advantage of this approach is that it is not affected by gloves, sweat, or surface contamination in the same way as capacitive sensing. The sensor can also be hidden within the steering wheel structure. The main limitations are that strain-based sensing detects mechanical loading rather than direct touch, and the signal may be strongly dependent on wheel structure, sensor placement, load path, and driver grip style. For this reason, structural strain sensing was considered a relevant but indirect HOD concept.

Radar-Based Presence Sensing

Radar-based presence sensors were identified as a potential non-contact sensing modality. These systems are used in other industries to detect human presence, movement, or micro-motion. In the steering wheel context, the transferable idea is to detect whether a hand is present near the steering wheel rather than whether it is physically touching the rim.

The main potential benefit is that radar can operate without visible light and does not require skin contact. It could therefore support a non-contact signal, which may be useful as a complementary sensing channel. Radar may also provide information about movement or micro-motion in the steering wheel area.

However, the study indicated that radar is less suitable as a standalone HOD solution if the requirement is strict contact confirmation. The sensor would need to distinguish hands on the wheel from hands near the wheel, passenger movement, body motion, and other cabin objects. In addition, the steering wheel area contains complex geometry and metallic structures, which may introduce multipath effects and false detections. Therefore, radar-based sensing was treated as a promising complementary concept.

Optical Touch and Shadow-Based Sensing

An optical shadow-based touch technology was also reviewed as a distinct non-capacitive principle. The technology detects touch or hover by using optical emitters and sensors to identify the shadow caused by an object. This was initially interesting because it provides a non-capacitive touch or proximity sensing approach and has been applied in screen-based interactive systems.

However, the transfer assessment showed that this principle is strongly tied to planar screen-like geometries. The sensing architecture normally relies on a defined surface and perimeter-based optical paths. A steering wheel has a three-dimensional toroidal geometry, soft trim, occlusion by hands, and limited space for optical emitter/receiver placement. Therefore, although the technology was logged as a distinct optical modality, it was not considered suitable for direct transfer to a steering wheel HOD system. It was retained in the raw exploration log as an excluded concept, mainly to document that optical non-capacitive touch systems had been considered.

Aerospace and Safety-Critical Enable Controls

The aerospace-related search did not reveal many examples of direct hand-touch sensing on aircraft yokes, sidesticks, or HOTAS controls. Most aviation control inceptor technologies focus on measuring force, torque, or control input direction rather than detecting whether the pilot's hand is physically touching the control. Therefore, aviation flight controls did not provide a direct equivalent to automotive HOD.

However, the search identified safety-critical "deadman" or hold-to-enable devices used in aviation ground operation, especially aircraft refuelling systems. These devices require an operator to continuously hold or actuate a trigger during a critical operation, and releasing the device causes the system to stop or enter a safe state. This introduced a different type of cross-industry concept: instead of passively inferring hands-on status, the steering wheel could include an explicit low-effort enable input.

Transferred to the steering wheel, this could be implemented as a low-effort deadman grip zone integrated into the rim. During Level 2 assisted driving, the driver would be required to maintain intentional contact or light grip activation with at least one hand. The advantage of this approach is that it provides a clear and diagnosable engagement signal and can be designed to be robust against gloves and moisture. The main concern is that it changes the HOD problem from passive sensing to explicit driver input, which raises questions regarding ergonomics, misuse, regulatory acceptance, and compatibility with the intended definition of hands-on readiness.

Summary of Transferable Modality Families

The cross-industry exploration resulted in several transferable modality families. These are summarized in Appendix A. The table presents the sensing families identified during the exploration and the main reason each family was either carried forward or excluded from later concept development.

ID	Added_By	Date	Area/Industry	Source_(product/paper/patent)	Link	What_it_detects_(touch/proximity/force/etc.)	Principle_(capacitive/FSR/optical/etc.)	Why_relevant_(1-2 lines)	Key_risks_(1-2)	Evidence_(proven/prototype)	RAG_(G/Y/R)
R-000	A	2026/2/12	Industrial HMI	Glove-capable capacitive touch/proximity panel (example family)	(paste link)	touch + proximity	capacitive / E-field	Designed for gloves/contamination; embedded behind overlay → analog to under-trim wheel electrodes	Water-film false triggers; needs shielding/layout for EMI	proven	
R-001	Wen	2026/2/13	Industrial HMI	Proximity/Projected Capacitive Sensor Technology PCAP for Touch Sensing Applications	https://www.nxp.com/docs/en/white-paper/PROXIMITYWP.pdf	touch + proximity	capacitive / E-field	Similiar tec as HOD.	water films EMC; needs shielding + algorithms	proven	G
R-002	Wen	2026/2/13	Industrial HMI	Industrial HMI for Gloved Hands: A Guide to Resistive, Capacitive, and IR Touchscreens	Industrial HMI for Gloved Hands: A Guide to Resistive, ... | Shunlongwei	touch, force detect(maybe)	Resistive/pressure	glove proof, less sensitive to moisture.	Cant detect multi-touch acc to info from net. Sensitivity to how the wheel is held (force distribution varies)	proven	Y
R-003	Wen	2026/2/13	Industrial safety switches	Cylindrical inductive safety switch for position monitoring	IME2S - Safety switches | SICK	Inductive sensing couples to conductive/metallic objects	Inductive proximity (metal target)	diagnostics/safety architecture pattern, not sensing modality	not for embedding around a steering wheel rim.	proven	R
R-004	Wen	2026/2/13	Smart home	What is A Presence Sensor and How Does it Work? Posted by OfficialAqara on March 20, 2025	https://eu.aqara.com/blogs/news/what-is-a-presence-sensor-and-how-does-it-work	presence/proximity + micro-motion	mmWave radar (presence sensing)	potential non-camera, non-contact hand-near-wheel signal (F2); complements capacitive/force for redundancy	multipath/ghost zones near metal wheel; false positives from passenger/body; power/EMC burden	proven (in home/rooms), transfer risk to automotive	Y
R-005	Wen	2026/2/13	Wearables / HMI / Force sensing components	Blog / supplier explainer: "Two types of Force Sensing Resistors (Shunt vs Thru)" (FSRexpert)	https://www.fsrexpert.com/two-types-of-force-sensing-resistors/?utm_source=chatgpt.com	Force / pressure (grip force proxy)	FSR (Force Sensing Resistor; piezoresistive)	Glove-proof under-trim grip detection concept (F3). Segment FSR strips around rim to detect "hands-on" via pressure distribution and support intent cues.	Force transmission through foam/leather may be inconsistent; drift/creep & temperature sensitivity → needs preload/stack-up design + calibration.	Prototype / supplier-level	Y
R-006	Wen	2026/2/17	Structural testing / load measurement / instrumentation	Blog / measurement primer: " What Is a Strain Gauge Sensor and How Does It Work?" (Dewesoft)	https://dewesoft.com/blog/measure-strain-and-pressure	Strain → force / deflection / torque proxy	Strain gauge (resistance strain gauge)	Non-capacitive grip detection: embed strain gauges in wheel rim/spokes to detect grip-induced deformation (F3); glove/wet robust.	Small signals + dependence on hand location; temperature/drift + adhesive aging; integration in wheel structure/assembly complexity.	Proven, transfer to steering wheel requires design validation	Y
R-007	Wen	2026/2/23	Optical touch for displays	What is ShadowSense™	What is ShadowSense?	touch/hover via IR shadow triangulation	optical (IR shadow-based)	non-capacitive hover/touch principle; potential proximity channel idea	requires perimeter frame + planar interaction surface; steering wheel is 3D curved + soft cover + occlusion → not transferable	Proven for screens; transfer unproven	Y
R-008	Wen	2026/2/23	Aviation ground operations (refuelling safety)	Liquip DMH100 Deadman Handle datasheet (PDF)	https://www.liquip.com/liquip.com/login/datasheets/Aviation/DMH100%20Datasheet.pdf	intentional continuous hold (operator presence/engagement)	electromechanical switch (sealed micro-switch)	proven safety interlock device requiring continuous operator action during critical operation; low-force, ergonomics-focused handle	transfer to steering wheel is an HMI enforcement concept (fatigue/bypass/compliance need evaluation)	Proven (aviation refuelling)	Y

Figure 4.4: Example of Cross-Industry Raw Log

4.2 Functional Analysis Results

Based on the black-box definition (inputs, disturbances, and outputs), the functional subfunctions, and the defined use cases and operating conditions, a set of derived requirements was formulated. The purpose of these requirements is to translate the operating envelope into expectations for concept assessment.

4.2.1 Inputs

Following the black-box logic, inputs were grouped into (i) physical interaction inputs and (ii) signal inputs.

Physical interaction inputs represent the measurable evidence generated by driver–wheel interaction. In our model, these include:

- contact force and grip pressure,
- micro-motions and vibration coupling during steering interaction,
- electrical interaction related to skin properties (e.g., capacitive or conductive coupling),
- thermal interaction (heat transfer between hand and wheel),
- optical interaction (e.g., occlusion/reflectance changes, if an optical modality is considered),
- acoustic/ultrasonic interaction (e.g., coupling changes, if applicable).

Signal/context inputs represent additional system information that may support decision stability, plausibility checks, and system integration. These include:

- steering angle and steering torque signals (from EPS),
- vehicle speed,
- time since last confirmed hands-on state,
- system self-test status.

The separation between physical interaction inputs and signal/context inputs clarifies that HOD should be primarily driven by interaction evidence, while vehicle signals can be used to support synchronization or confidence estimation.

4.2.2 Disturbances

To reflect real driving conditions and common failure mechanisms, disturbances were explicitly included in the black-box model. These disturbances capture factors that may alter sensing coupling, degrade signal quality, or bias classification, including:

- gloves (material and thickness),
- moisture and contamination (sweat, rain, condensation, hand cream, dirt),
- temperature extremes and thermal transients,
- electromagnetic interference (EMI), electrical noise, and supply variation,
- material aging and wear of steering wheel coverings,

- driver behavior variability (e.g., light touch, fingertip contact).

These items were included because they directly affect the reliability of interaction sensing and are typical sources of false positives/negatives or unstable state outputs.

4.2.3 Outputs

The outputs of the HOD function were defined to support both system-level integration and concept evaluation. The black-box outputs are:

- a discrete HOD state: Hands-On / Hands-Off / Uncertain,
- an optional confidence/probability measure associated with the state estimate,
- a diagnostic/fault indication and, when relevant, a degraded-mode flag.

Defining the "Uncertain" state and diagnostics at the black-box level helps we look more into thoes uncertainty handling and fault behavior.

4.2.4 Functional Diagram

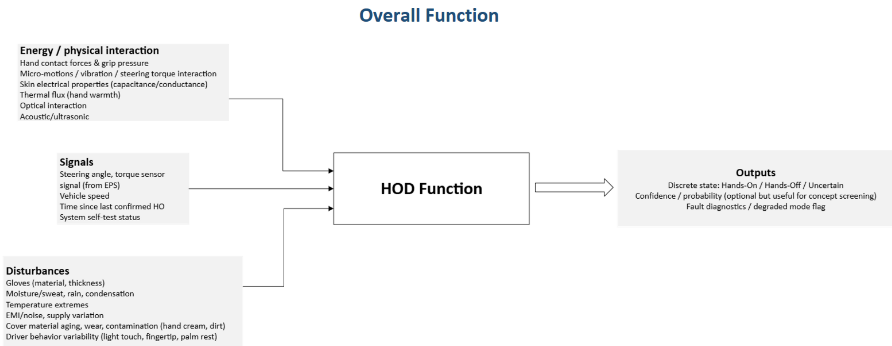


Figure 4.5: Functional Diagram

4.2.5 Subfunctions of the Detection Problem

The HOD function was decomposed into the following subfunctions:

- Sense driver–wheel interaction
- Acquire and condition signals
- Extract interaction features
- Classify HO/HOF/Uncertain
- Stabilize the state over time
- Output state, confidence, and diagnostics

This functional chain describes the minimum set of capabilities required to transform driver–wheel interaction into a HOD state as the diagram showed next.

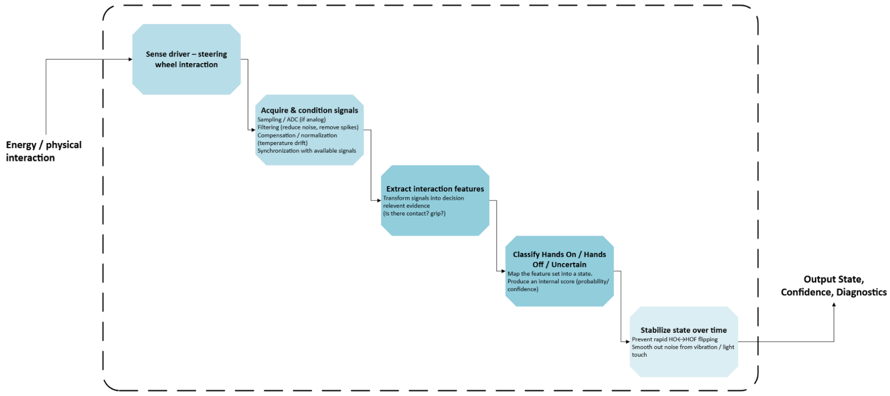


Figure 4.6: Sub-function Diagram

4.2.6 Description of each subfunction

Sense driver–wheel interaction
This subfunction captures measurable evidence of driver's interaction with the steering wheel. The output of this block is one or more raw signals representing interaction phenomena. The subfunction is defined at the level of "interaction evidence", so it remains compatible with concepts based on different physical principles.

Acquire and condition signals
This subfunction converts the raw sensing outputs into signals that for further computation. It includes sampling and basic signal conditioning steps such as filtering, normalization, compensation, and time synchronization. In the HOD context, this stage may also align sensing signals with available vehicle signals when they are used for timing support.

Extract interaction features
This subfunction transforms conditioned signals into decision indicators. The output could be a feature set that represents the interaction characteristics in a compact form. Typical feature categories include indicators that are related to contact presence, contact intensity and distribution of contact.

Classify the HOD State
This subfunction maps the extracted features to a HOD state. The classification logic may be implemented using thresholding, rule-based logic, or model-based/AI learning-based methods; however, at the functional level it is described as a mapping from features to states.

Stabilize the state over time
This subfunction ensures that the reported HOD state is stable and suitable for downstream vehicle systems. It addresses state oscillation that may occurred under road vibration, disturbances, or signal spikes. Functionally, it enforces temporal consistency rules so that the output does not change due to fluctuations.

Output state, confidence, and diagnostics
This subfunction provides the interface output required by the vehicle. It outputs the stabilized HOD state together with a confidence/quality indicator (if available) and diagnostic information such as fault flags. This subfunction is included because the output format could influence the evaluation of concepts at system level.

4.2.7 Use Cases and Operating Conditions

Use cases were organized into three groups: Hands-On (HO), Hands-Off (HOF) and mixed interaction patterns. For each use case, the main failure risk was noted to clarify why the case is relevant for HOD evaluation.

4.2.8 Hands-On (HO)

The HO patterns represent common ways drivers interact with the steering wheel. They were selected to capture variation in contact area, interaction intensity, and spatial distribution.

- Full grip: baseline HO with large contact area.
- Light fingertip touch: minimal contact area and low interaction intensity; relevant for sensitivity limits and false HOF risk.
- One-hand driving: contact distribution; stresses spatial coverage and dead-zone risk.
- low-grip contact: contact may exist without strong grip force.
- Micro-adjustments while driving: short and intermittent interactions.

4.2.9 Hands-Off (HOF)

The HOF cases represent conditions where the system should report hands off, including scenarios that may generate misleading interaction evidence and therefore cause false HO.

- Hands off: baseline HOF.
- Hands near the wheel without touching: stresses separation between proximity-like effects and actual contact.
- Hovering very close to the rim: increases coupling for some modalities and may cause false HO if not handled.
- Knee steering or other body contact: non-hand contact that may physically interact with the wheel.
- Object contact: stresses discrimination of hand contact versus other contacts.

4.2.10 Mixed interaction conditions

Some interaction patterns are not purely HO or HOF but reflect geometric or transition-related effects. Like Rim-only contact that stresses sensing coverage and sensitivity differences across wheel regions. Also the Re-grip and hand repositioning that will have transient signals and short loss of contact. These cases were included because driver hand placement is not fixed all the time.

4.2.11 Disturbances and operating conditions

Disturbances and operating conditions were documented to represent realistic variation in the driving environment and long-term usage. They were grouped into environmental, dynamic, electromagnetic, and durability factors.

Environmental and surface conditions

- Gloves: may alter sensing response.
- Moisture and contamination: may change surface properties.
- Temperature variation: may cause drift and affect baseline stability.

Dynamic driving conditions

- Road vibration and roughness: may transient fluctuations.
- Driver behaviour variability: different contact styles may change signal magnitude and pattern consistency.

Electromagnetic and electrical conditions

- EMI and ESD: may create spikes, leading to false state changes if not handled.
- Supply variation: may influence signal conditioning performance.

Durability conditions

- Wear of wheel materials: may change mechanical and surface properties over time.
- Contamination accumulation: may gradually reduce repeatability and shift signal baselines.
- Sensor faults: represent loss of sensing capability and require fault detection.

Functional requirements

- R1 — State output: The system shall output a discrete HOD state including Hands-On and Hands-Off. An Uncertain state shall be supported when evidence is insufficient or conflicting.
- R2 — Decision stability: The reported state shall be temporally stable and shall not exhibit rapid toggling due to transient fluctuations.
- R3 — Coverage of typical HO patterns: The system shall correctly detect common hands-on interaction patterns including full grip, one-hand contact, and low-intensity contact (e.g., light fingertip touch or palm resting).
- R4 — Coverage of typical HOF patterns: The system shall correctly detect hands-off conditions, including cases where hands are near the wheel but not touching.

- R5 — Non-hand contact handling: The system shall reduce false Hands-On detections caused by non-hand contacts such as objects or body contact (e.g., knee steering).
- R6 — Diagnostics and degraded behaviour: The system shall provide diagnostic information (fault indication) and define behaviour when reliable classification is not possible.

Robustness requirements under disturbances

- R7 — Glove robustness: The system shall maintain detection capability across variations in glove material and thickness.
- R8 — Moisture/contamination robustness: The system shall maintain acceptable performance under sweat, rain, and common surface contamination (e.g., hand cream, dirt).
- R9 — Temperature and drift robustness: The system shall tolerate temperature variation and drift effects such that the HOD output remains reliable over time and across operating temperatures.
- R10 — EMI and ESD: The system shall tolerate EMI, electrical noise, and supply variations without producing sudden state changes.

Dynamic operation requirements

- R11 — Transition behaviour: The system shall handle contact transitions (re-grip, repositioning) without unnecessary state oscillation.
- R12 — Response time feasibility: The system should support a response time that is compatible with vehicle-level HOD usage while maintaining stability (trade-off between sensitivity and persistence).

Integration and lifecycle requirements

- R13 — Mechanical integration feasibility: The concept shall be compatible with steering wheel geometry and typical covering materials without requiring unrealistic packaging assumptions.
- R14 — Electrical/ECU integration feasibility: The concept shall be compatible with vehicle electrical architecture in terms of wiring, interfaces, and signal processing feasibility.
- R15 — Durability and aging tolerance: The concept shall be tolerant to wear and aging of wheel materials and maintain repeatability over the expected lifecycle.
- R16 — Manufacturability: The concept should be feasible for high-volume manufacturing and support practical quality control and calibration strategies.

4.2.12 Evaluation Criteria for Concept Assessment

The evaluation criteria were derived from the requirements formulated in the previous subsection. Specifically, the black-box definition and the use-case and disturbance set were used to translate the operating envelope into explicit requirements.

These requirements were then transfer into criteria by grouping them into seven assessment categories and defining corresponding sub-criteria. As a result, each criterion in the concept scoring matrix is traceable to at least one derived requirement, and the overall criteria set provides a structured way to compare concepts with respect to both functional performance and feasibility constraints.

The criteria set consists of seven main categories, each decomposed into sub-criteria. This structure was selected to cover
(i) Detection capability
(ii) Robustness under realistic operating conditions,
(iii) Decision quality over time,
(iv) Suitability for multi-sensing fusion, and
(v) Feasibility constraints for vehicle integration and industrialization

4.2.13 Criteria set used in the concept scoring matrix

1. **Detection performance**
   - Hands-on sensitivity
   - Hands-off sensitivity
   - Non-hand contact rejection
   - Spatial coverage effectiveness

2. **Robustness to disturbances**
   - Glove robustness
   - Moisture robustness
   - Temperature and drift robustness
   - EMI/electrical noise robustness

3. **Dynamic decision quality**
   - Detection latency
   - Confidence/uncertainty output

4. **Fusion complementarity and redundancy benefit**
   - Do the three sensing channels provide genuinely different evidence?
   - Does the set reduce shared failure modes?
   - Does it offer direct + indirect + support, or mainly overlap?

5. **Engineering integration feasibility**
   - Mechanical integration feasibility
   - Electrical integration complexity
   - Durability and wear tolerance

6. System complexity and resource burden
- Compute requirement
- Power requirement
- Signal synchronization burden
- Calibration burden
- Fusion logic complexity

7. Industrialization feasibility
- Manufacturing scalability and quality control
- Cost
- Optional note: Supplier maturity/privacy/regulation

4.2.14 How the criteria were used

Each concept was assessed against the sub-criteria above using consistent scoring anchors and short written justifications. The use-case and disturbance definitions were used to interpret the detection and robustness criteria, while the functional chain informed what is required to achieve stable decision behaviour in system context. In addition, because the project direction includes multi-sensing fusion, fusion complementarity and shared-failure reduction were included explicitly as a main evaluation category.

4.3 Concept Candidate Development

The sensing principle identified during the technology exploration resulted in a total of 10 concepts. Each concept represents a distinct behaviour to steering wheel hands-on/hands-off detection. These concepts translate the abstract mechanism into the relevant steering wheel, capturing the type of interaction, integration into the STW, and the detection mode.

A key distinction in concept development is between contact based and non-contact-based detection, as this directly affects the detection certainty, robustness, and system complexity. Contact based concepts provide direct evidence of driver's hand interaction with the steering wheel, whereas non-contact-based detection extends detection capability by observing proximity or inferred inferred interaction signals and may introduce additional uncertainty.

The outcome of this process is a structured set of ten concept candidates (C1-C10), representing distinct regions of the explored sensing space.

4.3.1 Concept Candidate Overview

Following the concept development process, a set of ten concept candidates (C1-C10) was established. Each concept represents a distinct interpretation relevant to the steering wheel of one or more sensing principles identified during the technology exploration phase. The purpose of this section is to present a structured overview of these concept candidates before further visualization and combination.

To ensure consistency and comparability between concepts, each concept is described using a common set of attributes. These includes the concept identifiers and names, the underlying sensing principles, the intended integration architecture for the steering wheel and the direct or indirect detection of driver's hand on the steering wheel. In addition to this, each concept is characterized by its expected strength and the main risk or the limitations at the conceptual level.

The defined concepts cover the wide range of sensing principles. Several concepts are based on the direct sensing principle such as pressure and strain based approaches or the optical fibre approach, which completely relies on the driver's hand interaction with the steering wheel. The direct principle based concepts provide strong and immediate evidence of the contact or grip. Other concepts are based on indirect sensing principles such as radar, ultrasonic, or vision based approaches, which detects the presence of the driver's hand movement relative to the steering wheel.

4.3.2 Concept Visualization

To better understand the identified concepts, the candidates were translated into a steering wheel context and each concept was visualized at a conceptual level. The main purpose is to go beyond abstract description and provide intuitive visualization of how sensing principles can be physically integrated within the steering wheel.

The visualization focuses on three main aspects, the sensor placement, the interaction region, and the sensing mechanism. In addition, the interaction region is indicated to show whether the concept relies on direct hand contact on the steering wheel or through a detection of hands in proximity of steering wheel. The visuals also shows the type of signal generated, such as deformation, optical response, reflected waves, or electric field disturbances. As the first concept is capacitive sensing, it will not be mentioned but the 9 concepts are described below.

- **Pressure Distributed Sensing Mat (C2)**

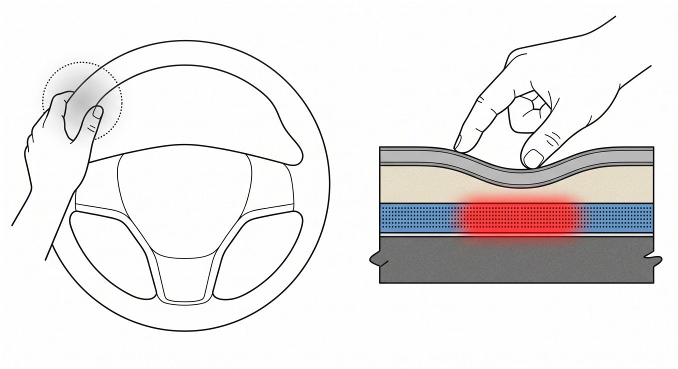


Figure 4.7: Pressure distributed sensing mat

The distributed pressure sensing mat is based on the resistive sensing principle and it is integrated beneath the artificial leather of the steering wheel. The pressure sensing mat spans the entire wheel surface and when the drivers hands are on the steering wheel then due to the pressure applied by the driver on the steering wheel the pressure sensing mat changes the electrical resistance. Thus, providing direct information about the grip location and intensity.

- **Strain Fabric (C3)**

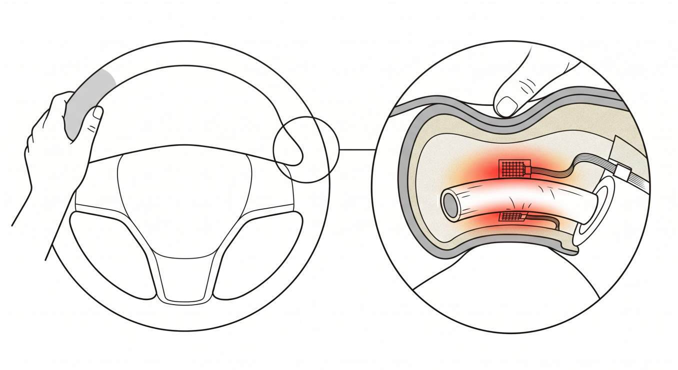


Figure 4.8: Strain Fabric sensing

A distributed strain sensitive fabric is integrated beneath the artificial leather or embedded within the steering wheel covering. The strain fabric operates on the principle of resistive strain change, where the mechanical deformation (either stretching or compression) caused by the grip on the steering wheel causes a change in electrical resistance. Changes in electrical resistance caused by hand grip enables detection of contact and grip-induced deformation.

- **Fluid Channel Sensing (C4)**

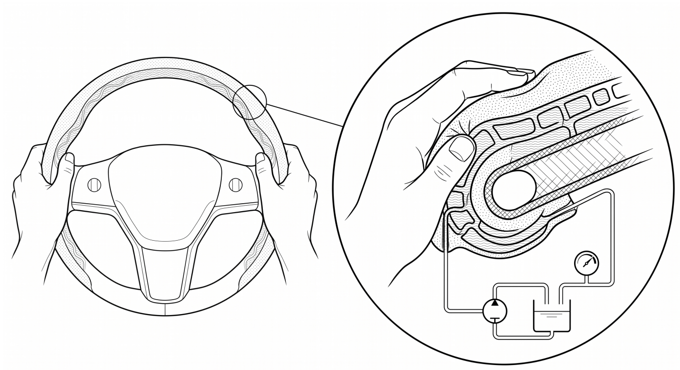


Figure 4.9: Fluid Channel Sensing

A network of fluid channels are integrated around the steering wheel rim and is forming a closed loop flow system which consists of a fluid reservoir, a pump, a inlet, and an outlet line along with a pressure sensor. When the driver holds the steering wheel, the applied force causes the fluid channels to decrease the cross sectional area, and thereby increasing the hydraulic flow resistance. This ultimately results in an increase in pressure within the system, which is detected by the pressure sensor and processed by the ECU to detect the HO/HOF. Another advantage is that the steering wheel can be heated by heating the circulating fluid, allowing heat transfer from the channels to the outer steering wheel surface, thereby providing a combined sensing and heating functionality.

- **Camera based sensing (C5)**

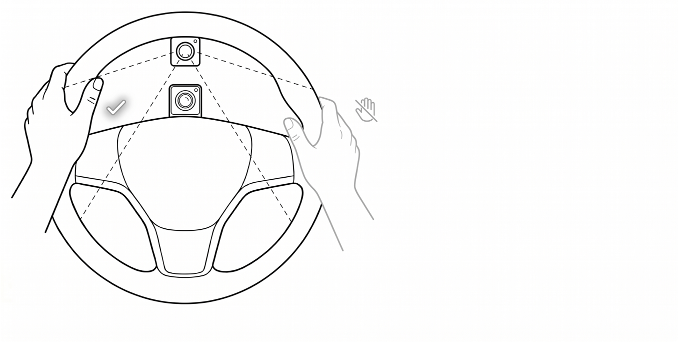


Figure 4.10: Camera based sensing

A cabin mounted or instrument panel mounted camera observes the steering wheel and the driver's hands. The hands on the steering wheel are detected using a computer vision technique and often supported by machine learning algorithms. The hands-on interaction is detected based on the spatial overlap or proximity between the hand and the steering wheel. The main advantage with the camera based sensing is that it does not interfere with the temperature mat which is used as the heating functionality of the steering wheel. So, there is not drift within the signal which is usually observed with the capacitive sensing.

- **Fiber Optics Based Sensing (C6)**

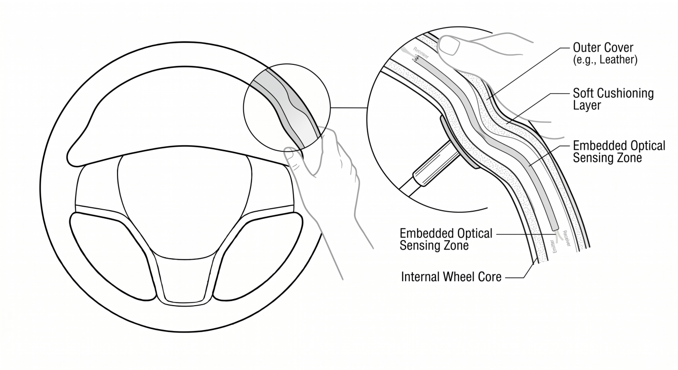


Figure 4.11: Optical Embedded Sensing

This concept uses a embedded optical fiber within the steering wheel structure to detect the driver's hand on the steering wheel. When deformation occurs due to the driver's hand, then there is a change in the light propagation within the optical medium. The mechanical compression or bending of the optical fiber alters the transmitted or received light intensity which is measured to detect the HO/HOF. Since the sensing principle is optical, it does not directly interfere with the temperature sensing control system and so the output is stable for detecting driver's hands on the steering wheel.

- **Ultrasonic Based Sensing (C7)**

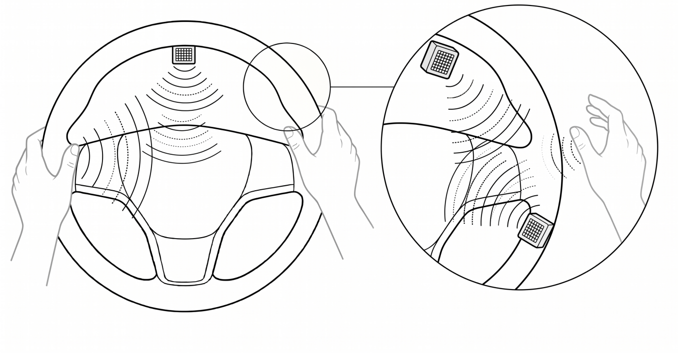


Figure 4.12: Ultrasonic Based Sensing

Ultrasonic sensing is based on emitting high frequency sound waves towards the steering wheel region and detecting the reflected signals from the driver's hand. The presence of a hand on the steering wheel is detected from the intensity of returned signal. The sensor is counted on the steering wheel for better working and coverage.

- **Radar Based Presence Sensing (C8)**

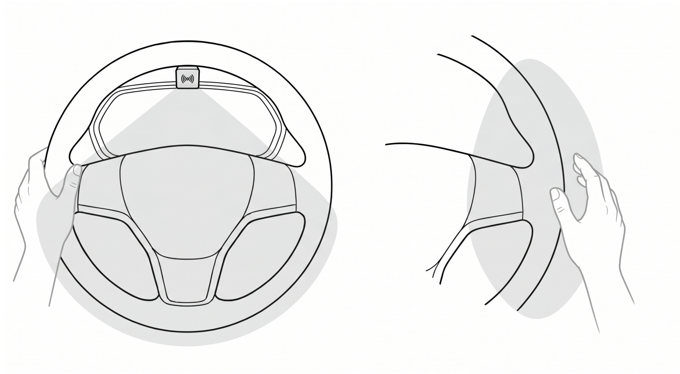


Figure 4.13: Radar Based Presence Sensing

This one is a non-contact sensing concept based on radar with millimeter-wave sensing directed toward the steering wheel interaction zone. Instead of detecting physical contact through the wheel surface, this concept observes hand-related reflections or movement patterns around the predefined wheel zone. The main advantage of this approach is that it is independent of lighting conditions and does not require camera-based image capture, making it potentially more privacy-friendly than vision-based sensing. It may also provide useful supporting evidence in a sensor-fusion architecture. However, the concept is expected to face challenges related to multipath reflection, clutter from nearby metallic structures, and the interpretation of close-range hand presence around the steering wheel.

- **Steering Torque Based Sensing (C9)**

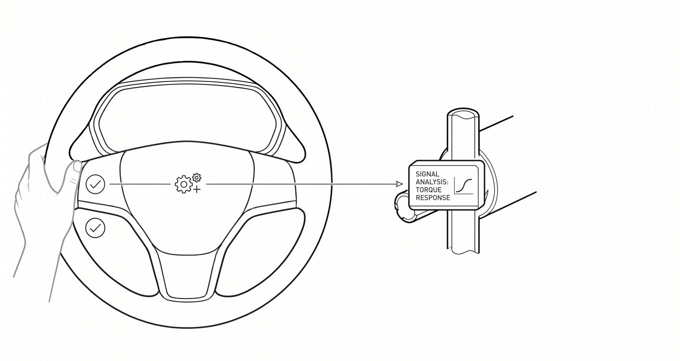


Figure 4.14: Steering Torque Based Sensing

This is an indirect sensing concept that infers hands-on/hands-off status from steering torque signals. Unlike direct touch-based concepts, it does not require additional sensing hardware on the steering wheel rim or surface. Instead, the detection logic is based on identifying steering behaviour, small driver inputs, or torque patterns that may indicate active driver engagement. This makes the concept attractive from an integration and packaging perspective, especially as a possible fusion input. Its main limitation is that it does not directly measure hand contact. As a result, it may confuse steering behavior with other kind of physical contact, and its reliability depends strongly on driving context, control strategy, and signal interpretation.

- **Conductive Foam Grip Sensing (C10)**

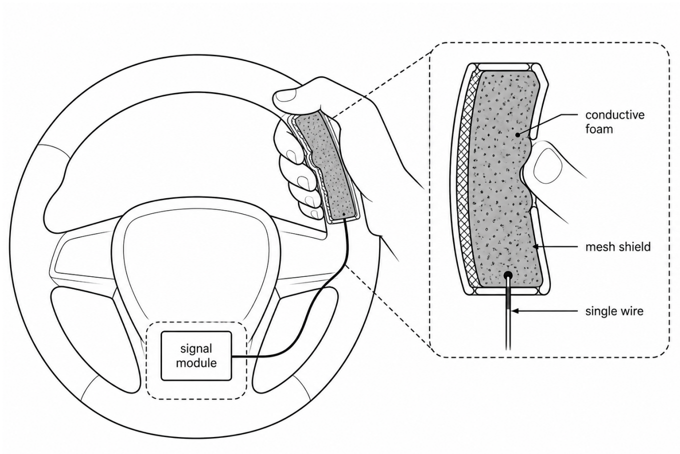


Figure 4.15: Conductive Foam Grip Sensing

This is a direct contact-sensing concept based on a soft conductive foam material integrated into the steering wheel grip area. The foam body is connected using only one signal wire and operates on the principle of Swept Frequency Capacitive Sensing (SFCS). When the driver touches, compresses, pinches, or grips the steering wheel, the deformation and contact condition of the conductive foam are expected to change the measured electrical response. This concept is attractive because of its simple hardware structure, soft material compatibility, and potential ability to capture both touch and deformation related interaction cues. However, it may be sensitive to environmental factors such as humidity, sweat, heat, material aging, EMC/ESD effects, and possible classifier drift under real operating conditions.

4.4 First-Round Screening Results

The first-round screening reduced the original ten concept candidates to seven concepts for the next stage. The concepts that were taken forward were distributed capacitive sensing, distributed pressure sensing, structural strain sensing, cabin camera hand-wheel interaction sensing, radar/mmWave wheel-zone hand presence sensing, steering-torque-based sensing, and single-wire conductive foam grip sensing.

Two concepts were excluded at this stage: micro fluid grip sensing and embedded optical grip sensing. In both cases, the overall screening outcome indicated lower suitability for continued development compared with the retained candidates. In addition, the ultrasonic wheel-zone hand presence sensing concept was not continued as an independent candidate. Instead, it was replaced by the radar/mmWave-based concept, which was judged to represent a stronger alternative within the same general sensing direction.

Selection Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
	(Reference)Distributed capacitive sensing layer	Distributed pressure sensing layer	Structural strain / rim deformation sensing	Microfluid grip-sensing	Cabin camera hand-wheel interaction sensing	Embedded optical grip sensing	Ultrasonic wheel-zone hand presence sensing	Radar / mmWave wheel-zone hand presence sensing	Steering-torque-based sensing	Single-wire conductive foam grip sensing
1. Functional relevance to HOD	0	+	+	-	-	0	-	-	-	0
2. Output stability and decision support	0	0	0	0	-	+	-	-	-	0
3. Robustness to user and environmental variation	0	+	+	+	+	+	0	+	+	+
4. Integration and transfer feasibility	0	0	-	-	+	-	+	+	0	0
5. Evidence maturity and credibility	0	0	-	-	+	-	0	0	0	-
6. Development and validation burden	0	0	0	-	+	-	+	+	0	0
7. Fusion complementarity potential	0	0	0	0	+	0	+	+	0	0
Sum +	0	2	2	1	5	2	3	4	1	1
Sum 0	7	5	3	2	0	2	2	1	4	4
Sum -	0	0	2	4	2	3	2	2	2	1
Net Score	0	2	0	-3	3	-1	1	2	-1	0
Rank	4	2	4	6	1	5	3	2	5	4
Continue?	Yes	Yes	Yes	No	Yes	No	Replaced by radar (C8)	Yes	Yes	Yes

Figure 4.16: First-Round Screening Matrix

The full matrix is provided in Appendix A. Following the first-round screening, the retained concepts were reorganized and relabeled for the fusion stage in order to simplify the combination-level analysis. The reduced set consisted of seven concepts:

- C1: Capacitive sensing
- C2: Resistive sensing
- C3: Strain fabric
- C4: Cabin camera
- C5: mmWave radar
- C6: Torque sensor
- C7: Foam sensing

4.5 Concept Combination Results

The project then shifted from evaluation of single concepts to evaluation of three-concept fusion architectures. This step was introduced because a single sensing principle is usually always come with some defect while the multi-sensing solution could compensate each other. The fusion direction was therefore used to explore whether complementary sensing behaviors could provide a more robust basis for concept evaluation.

From the seven retained concepts, all possible three-concept combinations were generated, resulting in 35 combinations. Before conducting a more detailed second-round screening, these combinations were first checked at architecture level. This pre-filter was used to remove combinations that were unsuitable in principle. The following architecture rules were applied:

- The combination should include at least one direct-contact or contact-related concept
- The combination should contain complementary sensing logic
- The architecture should be conceptually integrable
- The combination should not be unnecessarily redundant or overloaded

Architecture rules
1. Does it include at least one direct-contact or contact-related concept?
2. Does it include complementary sensing logic?
3. Is the combined architecture conceptually integrable?
4. Is it too redundant or too overloaded?

No.	Combination	Architecture Check	Comment
1	C1 + C2 + C3	Pass	
2	C1 + C2 + C4	Pass	
3	C1 + C2 + C5	Pass	
4	C1 + C2 + C6	Pass	
5	C1 + C2 + C7	Pass	
6	C1 + C3 + C4	Pass	
7	C1 + C3 + C5	Pass	
8	C1 + C3 + C6	Pass	
9	C1 + C3 + C7	Pass	
10	C1 + C4 + C5	Not Pass	too redundant
11	C1 + C4 + C6	Pass	
12	C1 + C4 + C7	Pass	
13	C1 + C5 + C6	Pass	
14	C1 + C5 + C7	Pass	
15	C1 + C6 + C7	Pass	
16	C2 + C3 + C4	Pass	
17	C2 + C3 + C5	Pass	
18	C2 + C3 + C6	Not Pass	too redundant
19	C2 + C3 + C7	Not Pass	too redundant
20	C2 + C4 + C5	Not Pass	too redundant
21	C2 + C4 + C6	Pass	
22	C2 + C4 + C7	Pass	
23	C2 + C5 + C6	Pass	
24	C2 + C5 + C7	Pass	
25	C2 + C6 + C7	Not Pass	too redundant
26	C3 + C4 + C5	Not Pass	too redundant
27	C3 + C4 + C6	Pass	
28	C3 + C4 + C7	Not Pass	too redundant
29	C3 + C5 + C6	Pass	
30	C3 + C5 + C7	Pass	
31	C3 + C6 + C7	Not Pass	too redundant
32	C4 + C5 + C6	Not Pass	too redundant
33	C4 + C5 + C7	Not Pass	too redundant
34	C4 + C6 + C7	Pass	
35	C5 + C6 + C7	Pass	

Figure 4.17: Concept Full Combinations

This architecture check reduced the set of combinations by excluding clearly redundant alternatives before the more detailed second-round screening was carried out.

4.6 Second-Round Screening Results

After the architecture-level check, the remaining fusion combinations were screened in a second round. In this stage, the we applied two different screening approaches independently. The purpose of doing this was to examine whether the retained combinations would remain similar even when the reduction logic differed.

Selection Criteria	C1 + C2 + C3	C1 + C2 + C4	C1 + C2 + C5	C1 + C2 + C6	C1 + C2 + C7
1. Complementarity of sensing evidence	0	+	+	+	0
2. Expected robustness through redundancy	0	0	0	0	0
3. System integration feasibility	0	+	+	+	0
4. System complexity / calibration burden	0	0	0	0	0
5. Value for HO / HOF / Uncertain classification	0	+	+	0	0
Sum +	0	3	3	2	0
Sum 0	5	1	2	3	5
Sum -	0	1	0	0	0
Net Score	0	4	4	3	0
Rank	4	1	1	2	4
Continue?	No	Yes	Yes	Yes	No

Figure 4.18: Part of the Second Screening Matrix

The full matrix is provided in Appendix A. The independently retained sets were then compared. Although the two results were not identical, the overlap between them was substantial. This overlap was used as an indicator that the retained combinations were not highly dependent on one single screening logic.

The combinations retained were then taken forward to the scoring stage. These ten common combinations were:

- C1 + C3 + C4
- C1 + C3 + C5
- C1 + C3 + C6
- C1 + C4 + C6
- C1 + C4 + C7
- C1 + C6 + C7
- C3 + C4 + C6
- C3 + C5 + C6
- C4 + C6 + C7
- C5 + C6 + C7

This common retained set formed the basis for the following concept scoring exercise.

4.7 Concept Scoring Results

The scoring exercise produced a ranked comparison of the ten shortlisted fusion combinations. Three combinations were selected for continuation based on their total score and overall balance across the criteria:

- C4 + C6 + C7
- C1 + C6 + C7
- C1 + C4 + C6

The remaining combinations showed useful characteristics in some criteria, but did not achieve the same overall balance. In several cases, the limitations were linked to weaker complementarity, lower expected robustness, or higher complexity relative to the benefit gained from the combination.

		C1 + C3 + C4		C1 + C3 + C5		C1 + C3 + C6		C1 + C4 + C6		C1 + C4 + C7	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
1. Detection performance	**25%**	4	1	4	1	4	1	4	1	5	1.25
2. Robustness to disturbances	**20%**	3	0.6	3	0.6	3	0.6	4	0.8	4	0.8
3. Dynamic decision quality	**15%**	4	0.6	4	0.6	4	0.6	3	0.45	3	0.45
4. Fusion complementarity & redundancy benefit	**15%**	5	0.75	5	0.75	3	0.45	5	0.75	4	0.6
5. Engineering integration feasibility	**15%**	4	0.6	4	0.6	4	0.6	5	0.75	4	0.6
6. System complexity & resource burden	**7%**	2	0.14	2	0.14	4	0.28	3	0.21	3	0.21
7. Industrialization feasibility	**3%**	3	0.09	3	0.09	3	0.09	5	0.15	3	0.09
Total Score		3.78		3.78		3.62		4.11		4	
Rank		7		7		9		3		5	
Continue?								Pass			

		C1 + C6 + C7		C3 + C4 + C6		C3 + C5 + C6		C4 + C6 + C7		C5 + C6 + C7	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
1. Detection performance	**25%**	5	1.25	3	0.75	3	0.75	4	1	4	1
2. Robustness to disturbances	**20%**	4	0.8	4	0.8	4	0.8	5	1	5	1
3. Dynamic decision quality	**15%**	4	0.6	4	0.6	4	0.6	4	0.6	3	0.45
4. Fusion complementarity & redundancy benefit	**15%**	4	0.6	4	0.6	4	0.6	4	0.6	4	0.6
5. Engineering integration feasibility	**15%**	4	0.6	5	0.75	5	0.75	5	0.75	5	0.75
6. System complexity & resource burden	**7%**	4	0.28	3	0.21	2	0.14	4	0.28	3	0.21
7. Industrialization feasibility	**3%**	3	0.09	3	0.09	3	0.09	3	0.09	3	0.09
Total Score		4.22		3.8		3.73		4.32		4.1	
Rank		2		6		8		1		4	
Continue?		Pass						Pass			

C1	C2	C3	C4	C5	C6	C7
(Reference) Distributed capacitive sensing layer	Distributed pressure sensing layer	Structural strain / rim deformation sensing	Cabin camera hand-wheel interaction sensing	Radar / mmWave wheel-zone hand presence sensing	Steering-torque-based sensing	Conductive foam grip sensing

Figure 4.19: Concept Scoring Matrix

The full matrix is provided in Appendix A. The scoring results were therefore used to reduce the set to three final concept combinations for further discussion.

4.8 Industrial Cross-Check

After the scoring exercise had been completed, an additional scoring round was carried out with input from the Volvo supervisor engineer. There we considered the logic of investigator triangulation, where multiple evaluators are used to provide additional observations and conclusions, thereby reducing reliance on a single evaluator perspective[26].

The result of this follow-up assessment showed a high degree of overlap with the authors' own shortlist. Two of the three concept combinations identified in the industrial scoring were also included in the authors' final three combinations. This convergence increased confidence that the main outcome was reasonably stable across different evaluators and not only a result of the our own perspective.

At the same time, the fact that one shortlisted combination differed between the two outcomes shows that concept evaluation at this stage still contains a judgement-based component. This is consistent with the early and exploratory nature of the work, where several criteria had to be assessed qualitatively.

4.9 Shortlisted Concept Combinations

Based on the concept scoring results, three fusion combinations were shortlisted for final consideration: C4 + C6 + C7, C1 + C6 + C7, and C1 + C4 + C6.

C4 + C6 + C7 was ranked highest because it offered a strong combination of robustness, dynamic support, and integration feasibility. The combination also showed good complementarity between the included sensing principles.

C1 + C6 + C7 was retained because it combined direct-contact sensing with additional grip-related sensing support and achieved a high score in expected detection performance. This made it a strong candidate from a functional HOD perspective.

C1 + C4 + C6 was retained because it provided a balanced architecture that combined direct-contact sensing, contextual interaction sensing, and steering-related response sensing. It also performed well in integration and industrialization feasibility.

Taken together, the three shortlisted combinations represent different fusion directions rather than minor variations of the same solution logic. For this reason, they were considered suitable as the final outcome of the concept screening and scoring process and as the basis for the later discussion of strengths, limitations, and future work.

Considering the combinations then Capacitive sensing (C1), Camera based sensing (C4), Steering Torque Based Sensing (C6), and Conductive Foam Grip Sensing (C7) out of which C1, C4, and C6 are already well established sensing technologies. So, the focus was completely diverted towards the PoC of the Conductive Foam Grip Sensing.

4.10 Proof-of-Concept Results

The concept selected for PoC (either conductive foam grip sensing) is based on the SFCS principle, where a single interacting wire is inserted within the foam to detect a variety of interaction conditions and detection including light or firm touches, gripping, hard presses, and even hand detection through gloves or without any physical contact at all. The implementation of PoC was inspired by the open source approach mentioned in [19]. The SFCS PoC is achieved by using an Arduino Mega 2560 combined with some passive components to achieve the swept frequency and signal acquisition. The circuit diagram was considered from [19] (figure 4.20).

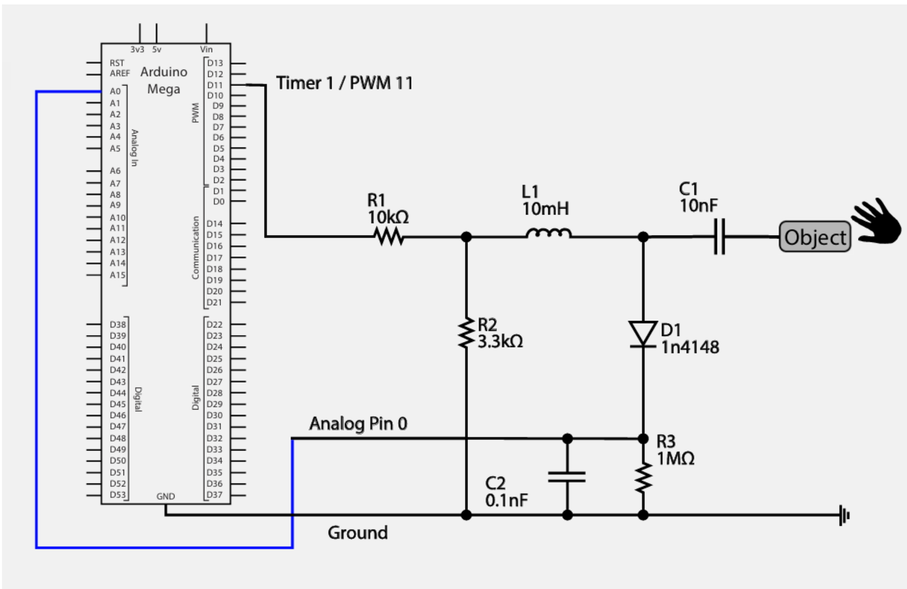


Figure 4.20: SFCS Circuit Diagram

The components used for this setup are mentioned below.

- Arduino Mega 2560 Rev 3
- USB cable to connect Arduino to Laptop
- Breadboard
- Jumper cables
- Resistor-R1 (10kohm)
- Inductor-L1 (10mH)
- Capacitor-C1 (10nF)
- Resistor-R2 (3.3kohm)
- Diode-D1 (1n4148)
- Resistor-R3 (1Mohm)

- Capacitor-C2 (0.1nF)

The Arduino Mega 2560 generates a square wave excitation signal and the passive component combination of L1 & C1 which is also known as LC circuit/LC filtering/Resonant circuit converts the square wave into an approximate sinusoidal waveform suitable for Swept Frequency Capacitive Sensing (SFCS).

The actual setup after following the circuit diagram is shown in figure 4.21.

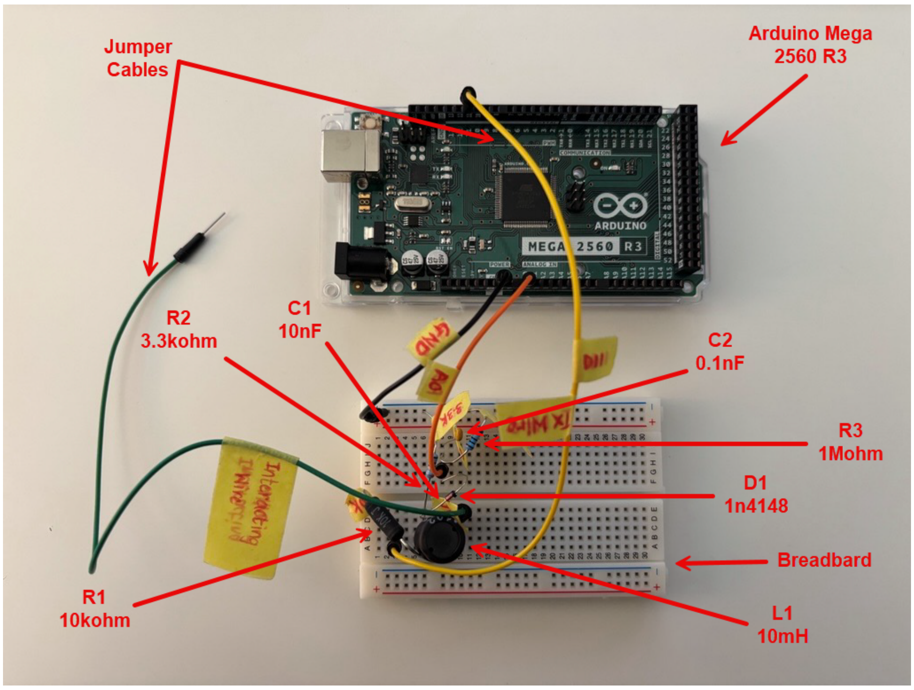


Figure 4.21: Actual PoC setup

As mentioned in 3.10.2, the variation in response was continuously observed on the Arduino IDE serial plotter. The X-axis represents the time/sample index, and the Y-axis represents the SFCS capacitive response profile/ADC Values (NOTE: The ADC is an Analog to Digital Converter having dimensionless digital number, which means no physical unit, and the ADC value represents the voltage level). The PoC setup is quite flimsy, so sometimes the values drift because of the loose connections.

In Arduino IDE serial plotter, multiple numerical values are printed on the same serial line. Therefore, each value represents a separate data stream that is plotted simultaneously. In this SFCS setup, the values can be interpreted as the ADC responses measured at different selected frequency steps within the frequency sweep. In simple terms, value 1 may represent the ADC response at one excited frequency, whereas the value 2 and on represent responses at other frequency. steps.

The following images show the SFCS capacitive response profile for different interactions.

Within the following graphs, each value represents a colour and, as mentioned, it represents the measured ADC response at different frequency points during the sweep.

The first test consists of pressing the tip of the sensing element between the fingers. When the sensing tip is not touched, the baseline SFCS capacitive response profile/ADC count does not vary much. The baseline ADC count ranges between 195 to 202 value, shown in figure 4.22.

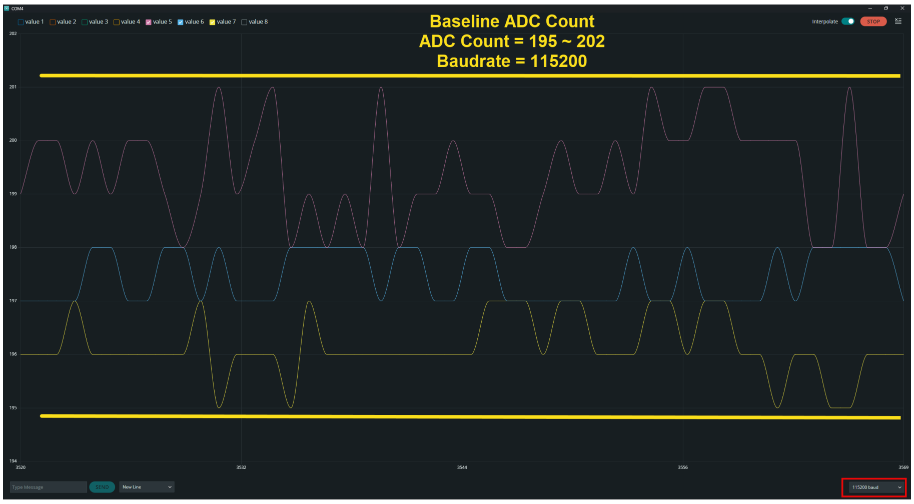


Figure 4.22: Baseline ADC count/Nominal SFCS capacitive response profile

It can be observed within the figure 4.23 that the amplitude varies considerably from the baseline level as soon as the sensing tip is pressed between the fingers. When the sensing tip is pressed the ADC count drops around 105 to 115 value.

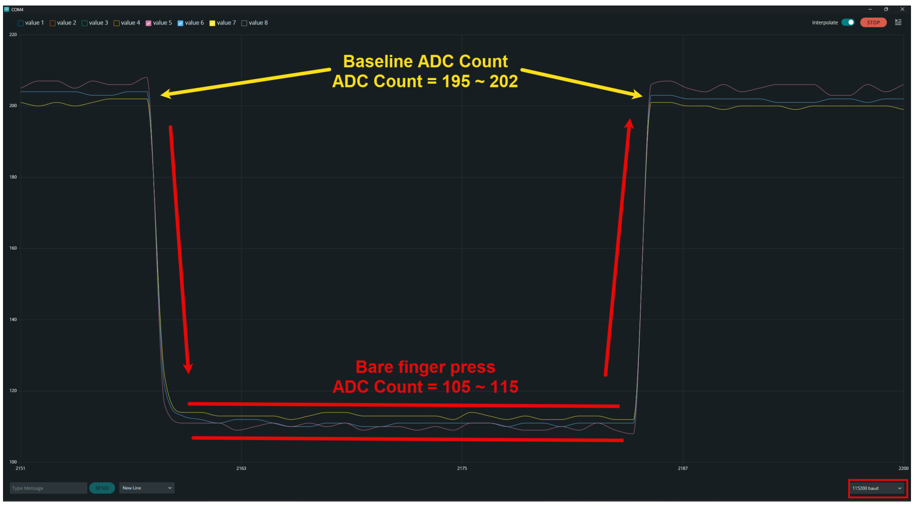


Figure 4.23: Sensing tip pressed between fingers

The second test consists of the interaction of metal plate with sensing tip. In this second test, two different kind of test were carried out.

- Metal plate 1mm apart from the sensing tip

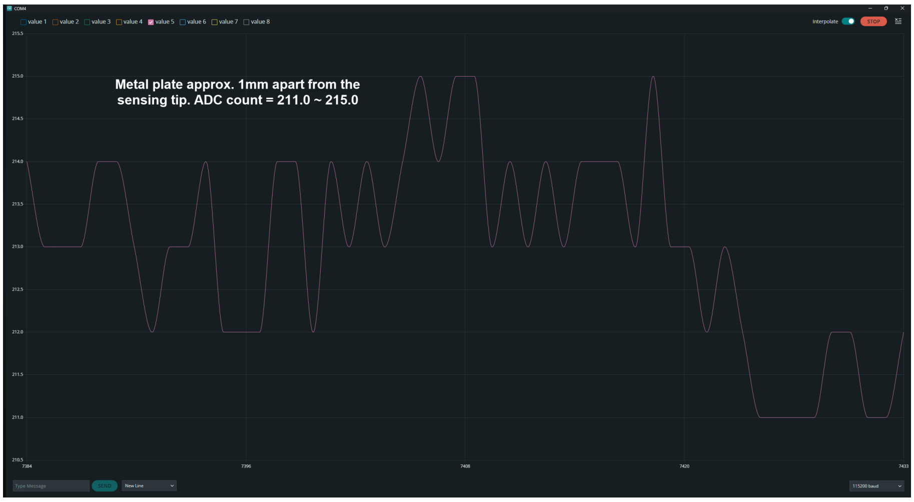


Figure 4.24: Metal plate approx. 1mm apart from sensing tip

It can be seen in the figure 4.24 that when the metal plate was kept approximately 1mm apart from the sensing tip then the ADC count ranges between 211 to 215 value. A slight increase in ADC count from the highest baseline ADC count can be observed.

- Sensing tip grabbed between two metal plates

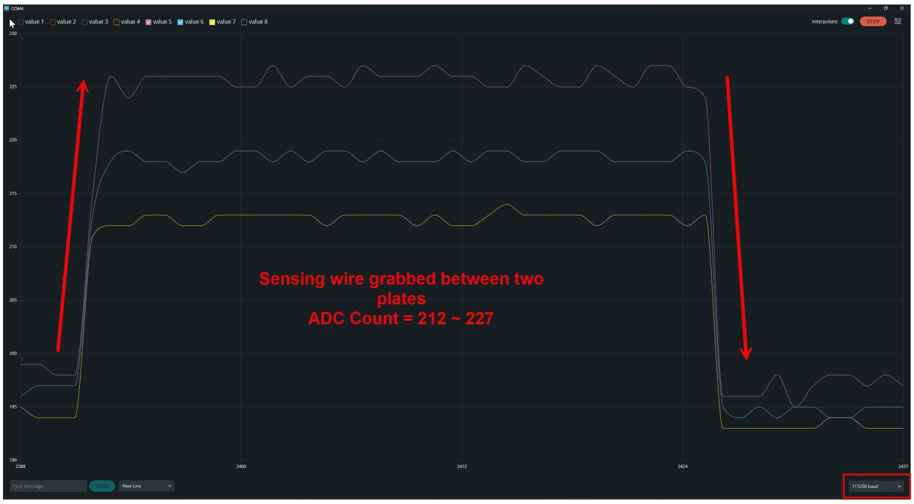


Figure 4.25: Sensing tip grabbed between two metal plates

It can be seen in figure 4.25 that when the sensing tip is grabbed between two metal plates then the ADC count ranges between 212 to 227 values. A significant increase in ADC count.

As the SFCS capacitive response profile was different for the pressed sensing tip and for the sensing tip between two metal plates, further tests were carried out with gloves to see the response profile. Gloves act like a barrier between the hand and the capacitive mat in the current system, so current systems needed to be tuned for it. Two types of gloves were used, thick and very thick gloves.

- Thick gloves

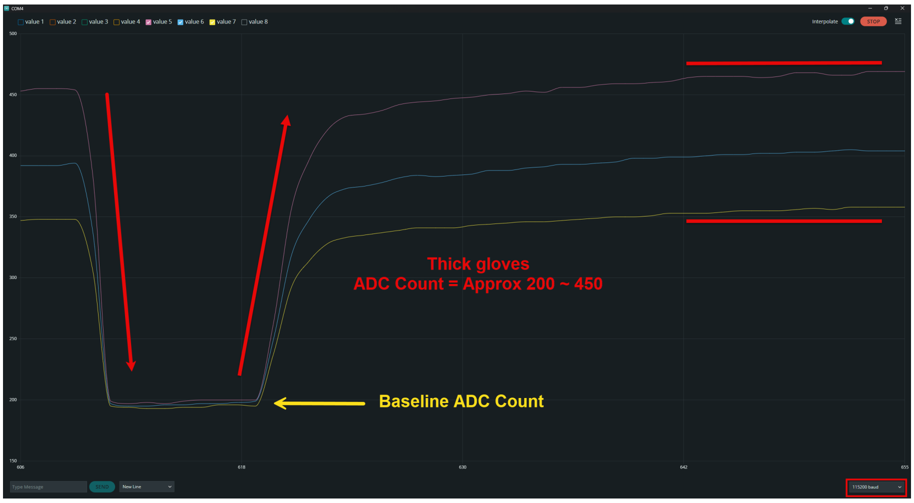


Figure 4.26: Thick gloves ADC Count

It can be seen in figure 4.26 that when thick gloves were used the response profile behaviour was different and the ADC count increased from 200 to 450.

- Very thick gloves

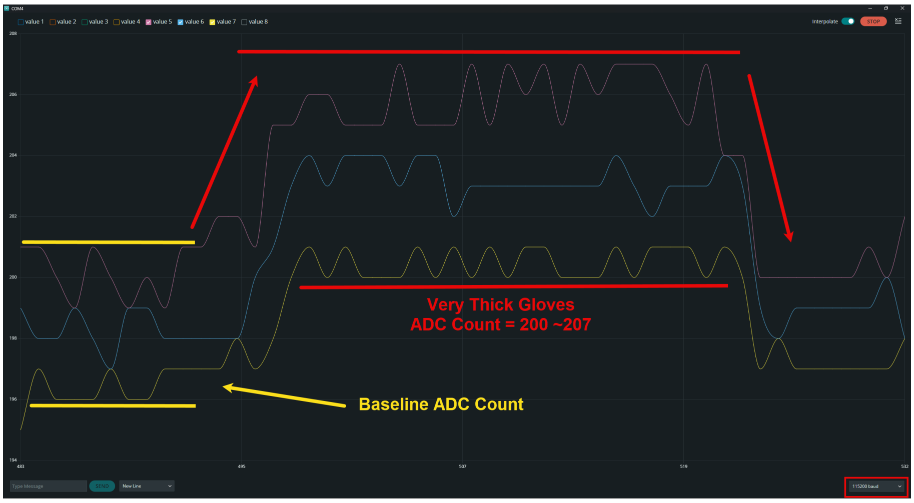


Figure 4.27: Very thick gloves ADC Count

It can be seen in figure 4.27 that when very thick gloves were used the response profile behaviour was different and the ADC count increased from 200 to 270. Compared to thick gloves, it is clearly visible that very thick gloves provided a large resistance and the ADC count was almost half the ADC count of thick gloves.

It can be concluded that the different interactions of the object with the sensing tip give different ADC count/SFCS capacitive response profiles.

The testing was performed qualitatively and focused on whether the sensing principle produced a noticeable difference between contact and non-contact cases.

5
Discussion

5.1 Answers to Research Questions

This section summarizes how the research questions were answered based on the results of the technology exploration, functional analysis, concept synthesis, screening, scoring, and proof-of-concept work.

5.1.1 Answer to Main Research Question 1

Research Question 1 asked:

What alternative sensing technologies currently exist that could potentially support the steering wheel hands-on/hands-off detection?

The study identified a broad set of sensing principles that could potentially support steering wheel hands-on/hands-off detection when interpreted from the perspective of driver–wheel interaction. These included capacitive and electric-field sensing, impedance-related sensing, mechanical force, pressure and strain sensing, optical and vision-based sensing, ultrasonic and acoustic sensing, radar/mmWave sensing, steering-system signal inference, and material-based sensing such as conductive foam.

The results show that the HOD sensing space is broader than the sensing principles commonly associated with current steering wheel implementations. However, the relevance of these technologies differs. Contact-based and deformation-based technologies provide more direct evidence of driver-wheel interaction, while camera, radar, ultrasonic, and steering-system signals provide more contextual or indirect evidence. Therefore, the main answer to this research question is that several alternative technologies do exist, but their value depends on how well they can be translated into the steering wheel context and how they contribute to the HOD function.

5.1.2 Answer to Sub-Research Question 1.1

Research Question 1.1 asked:

What evaluation/screening criteria should be used to assess candidate sensing solutions for steering wheel hands-on/hands-off detection?

The thesis found that the evaluation and screening criteria should be derived from the functional requirements of the HOD task instead of from any of the single sensor technology. The functional analysis defined the HOD system as a function that must sense driver-wheel interaction, acquire and condition signals, extract interaction features, classify the state, stabilize the state over time, and output the state with confidence where relevant.

From this functional analysis,the use cases, disturbances, and operating conditions were defined. These included full grip, light fingertip touch, one-hand driving, low-grip contact, hands near the wheel without touching, hovering hands, knee steering, object contact, re-grip, gloves, moisture, contamination, temperature variation, vibration, EMI/ESD, material aging, and sensor faults. These conditions were then translated into requirements and finally into concept assessment criteria.

The final concept scoring matrix used seven main criteria:

- Detection performance
- Robustness to disturbances
- Dynamic decision quality
- Fusion complementarity and redundancy benefit
- Engineering integration feasibility
- System complexity and resource burden
- Industrialization feasibility

The criteria were weighted according to their importance in the concept-level evaluation. Detection performance received the highest weight, followed by tolerance to disturbances. Dynamic decision quality, fusion complementarity, and engineering integration feasibility were also given substantial weight because the thesis shifted toward multi-sensing HOD concepts. System complexity and industrialization feasibility were included with lower weights, since the project was exploratory.

The answer, therefore, is that candidate sensing solutions should be assessed using criteria that can reflect both HOD function and steering wheel operating conditions. The criteria should evaluate whether a concept can meet the basic HOD detection need and also assess its potential for sensing fusion, as well as the automotive industry regulations.

5.1.3 Answer to Sub-Research Question 1.2

Sub-Research Question 1.2 asked:

Which sensing solution appears most promising for further investigation, and why?

The thesis did not identify one single sensing principle as a complete replacement for current HOD solutions. Instead, the screening and scoring results showed that the most promising directions are fusion-based combinations of complementary sensing concepts.

After the first-round screening, the first 10 concept candidates were reduced to 7 for the fusion stage. These were relabelled as:

- C1: Capacitive sensing
- C2: Resistive sensing
- C3: Strain fabric
- C4: Cabin camera
- C5: mmWave radar
- C6: Torque sensor
- C7: Foam sensing

From these seven concepts, three-concept combinations were generated and screened. The final scoring results selected three combinations for further consideration:

- C4 + C6 + C7: Visual-Foam-Torque Fusion - VFT Fusion
- C1 + C6 + C7: Double Contact-Torque Fusion - DCT Fusion
- C1 + C4 + C6: Visual-Capacitive-Torque Fusion - VCT Fusion

The first combination, VFT Fusion, was ranked highest because it combined contextual hand-position information and direct grip/contact-related sensing from conductive foam. This gave the combination strong complementarity across several evidence types. However, it still needs further investigation regarding camera occlusion, real-time fusion logic, foam material robustness, signal stability, and integration feasibility.

The second combination, DCT Fusion, was promising because it combined established capacitive HOD logic with steering torque inference and conductive foam grip sensing. This creates a more contact-oriented architecture, where capacitive sensing and foam sensing provide local interaction evidence while torque sensing adds system-level engagement information. Its main uncertainty is whether the two contact-related sensing channels provide enough additional benefit relative to their integration complexity.

The third combination, VCT Fusion, was retained because it combines a mature contact-sensing principle, a contextual hand-position-sensing principle, and an indirect steering-system signal. This combination may be attractive from an integration and industrialization perspective because capacitive sensing, camera sensing, and steering torque signals are relatively established in the automotive industry, compared with more speculative material-based concepts. However, it does not include the conductive foam concept and therefore may provide less new grip-deformation information than the combinations that include C7.

The answer to this question is therefore that the most promising sensing solutions are the shortlisted fusion combinations rather than individual sensing technologies. Among the individual concepts, conductive foam grip sensing was selected for proof-of-concept work because it was the least established element in the final shortlist and required additional early investigation.

5.1.4 Answer to Main Research Question 2

Main Research Question 2 asked:

How can a multi-sensing approach improve the robustness of steering wheel hands-on/hands-off detection?

A multi-sensing approach can improve robustness by combining sensing principles with different strengths and failure modes. Contact-based sensing can provide direct evidence of physical interaction with the steering wheel, while camera-based sensing can provide spatial confirmation of hand position. Steering torque can provide system-level evidence of driver influence on the steering system.

This is particularly relevant in ambiguous cases such as light fingertip contact, hovering hands or gloved hand. In such cases, one sensing principle alone may produce misleading evidence. A fusion-based architecture can compare different evidence channels, increase confidence when signals are consistent, and apply uncertainty handling or conservative classification when signals conflict.

The answer to this research question is therefore that multi-sensing can improve HOD robustness by combining direct, contextual, and system-level evidence, provided that the selected sensors could offer real complementarity.

5.1.5 Answer to Sub-Research Question 2.1

Sub-Research Question 2.1 asked:

Which sensing technologies can complement each others to overcome the limitations of individual HOD sensing methods?

The concept screening and scoring results suggest that the most useful complementarity comes from combining direct interaction sensing with contextual or indirect sensing. The final shortlisted combinations show three main forms of complementarity.

First, capacitive sensing and conductive foam sensing can complement each other as contact-related sensing channels. Capacitive sensing is relatively mature and can detect proximity or contact based on electric-field interaction. Conductive foam sensing, based on swept-frequency capacitive sensing, may provide additional information related to touch, compression, pinch, or grip deformation. This can potentially improve the distinction between simple proximity, light touch, and more meaningful hand-wheel interaction.

Second, cabin camera sensing can complement steering-wheel-embedded sensing by providing spatial information. A camera-based concept can check whether the driver's hand is actually located near or on the steering wheel. This can help resolve cases where an embedded sensor detects ambiguous contact or where non-hand objects interact with the wheel. However, camera sensing also introduces uncertainties related to privacy, so it is more suitable as a complementary channel rather than a standalone HOD solution.

Third, steering torque sensing can complement both contact-based and non-contact sensing by providing system-level evidence of driver involvement. Torque signals do not directly detect hand contact, but they can indicate steering input, micro-corrections, or driver influence on the steering system. When combined with contact or camera-based evidence, torque information can help distinguish passive contact from active steering engagement.

The final combinations selected in this thesis reflect these complementarity patterns. VFT Fusion combines camera-based context, torque-based engagement inference, and foam-based grip/contact evidence. DCT Fusion combines capacitive contact/proximity sensing, torque-based engagement inference, and conductive foam grip sensing. VCT Fusion combines capacitive sensing, camera-based spatial confirmation, and steering torque inference.

The answer to this question is therefore that the most relevant complementary technologies are capacitive sensing, cabin camera sensing, steering torque sensing, and conductive foam grip sensing. The thesis results suggest that such complementary relationships are more promising than relying on any single sensing method.

5.2 Methodological Reflection

The methodology was based on a structured concept development and selection logic. The use of Ulrich's concept development approach was useful because the thesis dealt with an early-stage design problem where solutions had to be generated, organized, reduced, and compared. The distinction between concept generation, concept screening, and concept scoring helped maintain a logical flow from broad exploration to a more focused shortlist.

A strength of this approach is that it made the decision process explicit. Rather than selecting concepts based only on informal preference, the thesis used matrices, criteria, and comparative reasoning. This was particularly important because the sensing principles differed significantly. The structured approach also supported documentation of why certain concepts were merged, excluded, or retained for later fusion.

The cross-industry exploration added value by widening the search beyond the automotive HOD domain. Several relevant sensing ideas are not unique to steering wheels. Similar functional problems exist in industrial human-machine interfaces, medical electrodes, wearable sensing, aerospace controls, safety switches, and smart surfaces. These domains provided examples of how human presence, contact quality, grip, force, or interaction state can be detected under different constraints. This helped generate concepts that might not have appeared through an automotive industry search.

At the same time, the method has clear limitations. The concept evaluation was partly qualitative and judgment-based. Since no complete physical prototypes were built and tested, several ratings had to be based on expected behavior, reported properties in literature, patent descriptions, or engineering interpretation. This is acceptable for early concept evaluation, but it limits the strength of the conclusions. Some criteria, such as integration complexity or robustness to disturbance, can only be fully assessed through detailed design, simulation, and prototyping.

The lack of physical validation also means that the scoring results should be treated as decision support. The matrices helped compare concepts systematically, but they cannot replace real testing. Weighting choices also influenced the final ranking. Although the criteria were derived from the earlier functional and requirement analysis, different weightings could lead to different final priorities. The results are therefore useful as a structured basis for selecting future development directions.

5.3 Industrial Relevance for Volvo Cars

For Volvo Cars, the shortlisted concept combinations can be interpreted as possible directions for future hands-on/hands-off detection research. The current industrial relevance lies less in immediate implementation and more in identifying where future sensing architectures may offer advantages over existing solutions.

The shortlist indicates that future R&D should not focus only on replacing one sensor with another. A more better way of doing this is to investigate how those sensing principles can be integrated into a robust detection architecture. Concepts that combine direct interaction evidence with additional contextual evidence may be more promising than concepts relying on only one physical phenomenon. For example, a force-related signal can provide direct information about driver interaction, while another sensing channel may help confirm hand position, compensate for disturbance, or improve classification confidence.

Some concept families appear attractive but uncertain. Vision-based approaches may provide rich information about hand position and posture, but their feasibility depends on packaging, lighting, computation, and customer acceptance on privacy. Pressure-based concepts may be easier to understand physically, but their ability to distinguish valid hand contact from other loads must be verified.

The next industrial step would therefore be feasibility testing. Volvo Cars would need to evaluate selected combinations through controlled experiments using representative steering wheel geometries, materials, trim layers, and vehicle operating conditions. Testing should include different drivers, grip styles, hand positions, gloves, moisture conditions, temperature variation, vibration, steering input, and false-contact scenarios. The aim should be to determine whether the shortlisted combinations improve detection confidence, reduce false positives or false negatives, and provide stable state output compared with a baseline system.

A staged validation approach would be suitable. First, bench-level sensor feasibility tests could be used to confirm whether each sensing channel produces measurable and separable signals. Second, simplified steering wheel prototypes could be used to test signal quality. Third, vehicle tests could evaluate system-level performance under realistic use cases. Only after these stages would it be meaningful to assess manufacturability, cost, supplier integration, and compliance with production requirements.

5.4 Limitations

This thesis has several limitations that affect how the results should be interpreted. First, the work did not include full experimental validation. The concepts were evaluated at a conceptual level, based on literature, patents, cross-industry references, and engineering knowledge. As a result, the final shortlist identifies promising directions, but does not demonstrate verified detection performance.

Second, the thesis did not include a full costed industrialization study. Cost was considered in the evaluation with a relatively low weight, which was appropriate for the early exploratory aim of the project. However, production feasibility, supplier availability, assembly implications, durability, and lifecycle cost were not assessed in detail. These factors would be critical in a later product development phase.

Third, the concept ratings were partly based on expert judgment and interpretation. Although the use of structured matrices improved transparency and consistency, some ratings still depended on how the evaluators interpreted the available evidence. This introduces subjectivity. The use of independent evaluation between evaluators reduced this risk to some extent, but it cannot remove it completely.

Fourth, the literature, patent, and cross-industry searches may still be incomplete. The sensing space is broad, and relevant concepts may exist in unpublished industrial work, or in domains that were not covered by the search strategy. The thesis therefore cannot claim to have identified every possible hands-on/hands-off detection principle. It provides a structured and traceable exploration within the selected scope.

Fifth, the final concepts were not compared directly against a complete production-grade benchmark system. Existing industrial HOD systems are likely optimized through supplier development, calibration, validation, and vehicle integration. Comparing early-stage concept combinations against such systems would require access to benchmark hardware, performance data, and standardized test conditions. Since this was outside the scope of the thesis, the results should be interpreted as concept-level potential rather than confirmed superiority over current solutions.

Overall, the limitations mean that the thesis should be read as an early-stage concept exploration and evaluation study. Its main value is in structuring the hands-on/hands-off detection problem, widening the sensing design space, and identifying fusion-based directions for further investigation. The work does not conclude that the shortlisted concepts are ready for implementation, but it provides a reasoned basis for selecting which directions should be tested next.

6
Conclusions

This chapter concludes the thesis based on the technology exploration, functional analysis, requirement derivation, concept candidate development, concept screening, concept scoring, industrial cross-check, and proof-of-concept work presented in the previous chapters.

6.1 Final Concluding Statement

The study identified and evaluated several sensing principles with potential relevance for steering wheel HOD, including contact-based, deformation-based, optical, acoustic, radar-based, torque-based, and conductive foam sensing approaches. Through functional analysis, screening, and scoring, these principles were translated into steering-wheel-relevant concept candidates and reduced to a smaller set of promising fusion-based directions.

The results suggest that a single sensing principle is unlikely to address all relevant HOD use cases and disturbances. Instead, the most promising directions combine complementary evidence channels, such as direct contact or grip evidence, spatial hand-position evidence, and steering-input evidence. This supports the conclusion that future HOD development may benefit from sensor-fusion architectures, especially for ambiguous cases such as gloved hands, light contact or object contact.

The thesis also showed that functional decomposition can support early-stage concept evaluation by separating the HOD problem from specific sensor technologies. This made it possible to compare different sensing principles more systematically and to derive evaluation criteria from the required detection functions and operating conditions.

The exploratory proof-of-concept provided early observations of selected sensing behaviour. Its main value is to support future feasibility discussions and to indicate what should be tested in more realistic prototypes.

Overall, the thesis contributes a structured technology landscape, a documented concept evaluation process, and a shortlist of alternative sensing-fusion directions for future steering wheel HOD development. Future work may focus on mature prototypes, realistic disturbance testing, sensor-fusion logic, and automotive integration aspects such as packaging, durability, manufacturability, and compliance.

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A
Concept Screening and Scoring Matrices

This appendix presents the full matrices used during the concept selection process. The matrices are included to provide traceability for the screening and scoring results discussed in the main text.

ID	Added_By	Date	Area/Industry	Source_(product/paper/patent)	Link	What_it_detects_(touch/proximity/force/etc.)	Principle_(capacitive/FSR/optical/etc.)	Why_relevant_(1-2 lines)	Key_risks_(1-2)	Evidence_(proven/prototype)	RAG_(G/Y/R)
R-000	A	2026/2/12	Industrial HMI	Glove-capable capacitive touch/proximity panel (example family)	(paste link)	touch + proximity	capacitive / E-field	Designed for gloves/contamination; embedded behind overlay → analog to under-trim wheel electrodes	Water-film false triggers; needs shielding/layout for EMI	proven	
R-001	Wen	2026/2/13	Industrial HMI	Proximity/Projected Capacitive Sensor Technology PCAP for Touch Sensing Applications	https://www.nxp.com/docs/en/white-paper/PROXIMITYWP.pdf	touch + proximity	capacitive / E-field	Similiar tec as HOD.	water films EMC; needs shielding + algorithms	proven	G
R-002	Wen	2026/2/13	Industrial HMI	Industrial HMI for Gloved Hands: A Guide to Resistive, Capacitive, and IR Touchscreens	Industrial HMI for Gloved Hands: A Guide to Resistive, ... | Shunlongwei	touch, force detect(maybe)	Resistive/pressure	glove proof, less sensitive to moisture.	Cant detect multi-touch acc to info from net. Sensitivity to how the wheel is held (force distribution varies)	proven	Y
R-003	Wen	2026/2/13	Industrial safety switches	Cylindrical inductive safety switch for position monitoring	IME2S - Safety switches | SICK	Inductive sensing couples to conductive/metallic objects	Inductive proximity (metal target)	diagnostics/safety architecture pattern, not sensing modality	not for embedding around a steering wheel rim.	proven	R
R-004	Wen	2026/2/13	Smart home	What is A Presence Sensor and How Does it Work? Posted by OfficialAqara on March 20, 2025	https://eu.aqara.com/blogs/news/what-is-a-presence-sensor-and-how-does-it-work	presence/proximity + micro-motion	mmWave radar (presence sensing)	potential non-camera, non-contact hand-near-wheel signal (F2); complements capacitive/force for redundancy	multipath/ghost zones near metal wheel; false positives from passenger/body; power/EMC burden	proven (in home/rooms), transfer risk to automotive	Y
R-005	Wen	2026/2/13	Wearables / HMI / Force sensing components	Blog / supplier explainer: "Two types of Force Sensing Resistors (Shunt vs Thru)" (FSRexpert)	https://www.fsrexpert.com/two-types-of-force-sensing-resistors/?utm_source=chatgpt.com	Force / pressure (grip force proxy)	FSR (Force Sensing Resistor; piezoresistive)	Glove-proof under-trim grip detection concept (F3). Segment FSR strips around rim to detect " hands-on" via pressure distribution and support intent cues.	Force transmission through foam/leather may be inconsistent; drift/creep & temperature sensitivity → needs preload/stack-up design + calibration.	Prototype / supplier-level	Y
R-006	Wen	2026/2/17	Structural testing / load measurement / instrumentation	Blog / measurement primer: "What Is a Strain Gauge Sensor and How Does It Work?" (Dewesoft)	https://dewesoft.com/blog/measure-strain-and-pressure	Strain → force / deflection / torque proxy	Strain gauge (resistance strain gauge)	Non-capacitive grip detection: embed strain gauges in wheel rim/spokes to detect grip-induced deformation (F3); glove/wet robust.	Small signals + dependence on hand location; temperature/drift + adhesive aging; integration in wheel structure/assembly complexity.	Proven, transfer to steering wheel requires design validation	Y
R-007	Wen	2026/2/23	Optical touch for displays	What is ShadowSense ™	What is ShadowSense?	touch/hover via IR shadow triangulation	optical (IR shadow-based)	non-capacitive hover/touch principle; potential proximity channel idea	requires perimeter frame + planar interaction surface; steering wheel is 3D curved + soft cover + occlusion → not transferable	Proven for screens; transfer unproven	Y
R-008	Wen	2026/2/23	Aviation ground operations (refuelling safety)	Liquip DMH100 Deadman Handle datasheet (PDF)	https://www.liquip.com/liquip/login/datasheets/Aviation/DMH100%20Datasheet.pdf	intentional continuous hold (operator presence/engagement)	electromechanical switch (sealed micro-switch)	proven safety interlock device requiring continuous operator action during critical operation; low-force, ergonomics-focused handle	transfer to steering wheel is an HMI enforcement concept (fatigue/bypass/compliance need evaluation)	Proven (aviation refuelling)	Y

Raw Source ID	Source Type	Industry	Original Example	Sensing Principle	Detected Variable	Key Strength	Key Limitation	Steering Wheel Translation	Concept Family	ML/DL	Comments
P-01	Patent	Automotive	Roof-mounted infrared camera system monitoring whether driver hands are on the steering wheel	Infrared camera + image recognition / CNN-based hand detection	Driver hand presence on steering wheel; hands-on / hands-off state	No modification to steering wheel structure; suitable for existing vehicle platforms; non-contact sensing; claimed low cost and good adaptability	Depends on line of sight, image quality, lighting/occlusion conditions, and model robustness; contact is inferred visually rather than directly measured	Roof-mounted or cabin-mounted IR camera observing steering wheel region to classify hands-on/off	M5 — Optical / Vision-based	ML/DL	**C5 Merged**
P-02	Patent	Automotive	Driver monitoring system inferring hand-wheel interaction from image sensor, body keypoints, and contextual driver/seat/dynamics information	Vision-based driver monitoring with keypoint extraction and driver model; hand-wheel state inferred from image + driver/seat/dynamics information	Hands-on / hands-off condition, with force/contact state inferred from body pose, hand vicinity, seat information, and vehicle dynamics	Rich contextual information; can use existing cabin sensing and driver monitoring inputs; no steering wheel hardware integration required	Indirect inference rather than direct physical touch sensing; high algorithmic complexity; sensitive to occlusion, pose estimation quality, and system calibration	Cabin camera or image sensor estimating hand-wheel interaction from driver pose and contextual signals	M5 — Optical / Vision-based		**C5 Merged**
P-03	Patent	Automotive	Hands-on/off detection based on steering variables such as torque, evaluated with machine learning	Machine-learning estimation from steering-related signals, especially steering torque / steering variables, optionally with domain logic and test torque	Hands-on / hands-off state estimated from steering torque or other steering variables	Does not require capacitive sensor or camera; avoids extra wheel-mounted touch hardware; potentially easier packaging in existing steering system	Detection is indirect; likely sensitive to driver behavior, road conditions, and steering context; may struggle with weak hand input or ambiguous torque patterns	Hands-on/off estimation from steering torque / steering variables using ML, potentially as a software-based or steering-system-based concept	M3 — Mechanical force / Pressure / Strain		**C9 Merged**
P-04	Patent	Automotive	Optical-effect touchpad integrated into a steering wheel for touch and hand interaction detection	Embedded optical sensing using a light source, optical waveguide / deformable optical element, and camera-based image capture of deformation/light pattern changes	Hand/finger touch position, pressing direction, gesture-like movement, and contact on steering wheel touch areas	Embedded in steering wheel; potentially rich spatial interaction data; can detect touch behavior without relying on electric-field sensing	Mechanically and optically complex; integration and durability risk; likely sensitive to packaging, contamination, and calibration	Embedded optical touch/grip sensing zones integrated into steering wheel rim or spoke, using light propagation/deformation changes to infer contact	M5 — Optical / Vision-based		
P-05	Patent	Flexible sensors	Piezoresistive foam-based flexible pressure sensor for curved or bendable surfaces, with steering wheel shown as an application example	Piezoresistive foam layer whose resistance changes under applied pressure, combined with electrode array	Applied pressure / touch pressure distribution	Large-area flexible sensing potential; direct pressure-related signal; suitable for soft/curved surfaces; patent explicitly shows steering wheel applicability	Measures pressure rather than pure hand presence; possible drift, hysteresis, durability, and material aging concerns; requires layered integration under surface	Pressure-sensitive layer under steering wheel cover for grip/contact detection across wheel surface or grip zones	M3 — Mechanical force / Pressure / Strain		**C2 Merged**
R-001	Product	Industrial HMI	Projected capacitive proximity/touch sensing for industrial interfaces	Capacitive / electric-field sensing	Touch + proximity	Mature and proven; directly relevant to hands-on/off style detection; supports non-mechanical sensing	Sensitive to water films, EMC, and shielding/calibration requirements	Distributed capacitive electrodes under steering wheel cover for touch/proximity-based hands-on detection	M1 — Electric-field / Capacitive		**C1 Kept as candidate evidence**
R-002	Product	Industrial HMI	Resistive and IR touchscreen approaches for gloved-hand industrial operation	Resistive / pressure-based touch sensing	Touch, possibly force-related contact	Glove-compatible; less moisture-sensitive than capacitive; useful as non-capacitive contact logic	Usually designed for planar touch interfaces; limited multi-touch capability; signal depends on force distribution	Pressure-sensitive grip zones or under-cover pressure layer for glove-tolerant hand-contact detection	M3 — Mechanical force / Pressure / Strain		**C2 Merged**
R-003	Product	Industrial safety switches	Inductive safety switch for position monitoring of conductive/metallic targets	Inductive proximity sensing	Presence/position of metal target	Robust and proven in safety architecture; useful as benchmark for safety-oriented sensing logic	Detects metal targets rather than human hand contact; poor transferability to soft steering wheel rim context	Not a primary steering wheel HOD concept; mainly a reference for safety-oriented architecture thinking	M7 — Radar / mmWave		**Reference / fusion inspiration Excluded**
R-004	Product	Smart home	mmWave presence sensor for human presence and micro-motion detection in rooms	Radar / mmWave presence sensing	Presence, proximity, micro-motion	Non-contact and non-camera; potentially useful as complementary hand-near-wheel signal	Multipath/ghost zones near metal wheel; false positives from passenger/body; transfer risk from room-scale to cockpit	Short-range mmWave sensing toward steering wheel region for non-contact hand presence estimation	M7 — Radar / mmWave		**C8 Merged**
R-005	Product	Industrial HMI	Force Sensing Resistors (FSR) for pressure/force detection	FSR / piezoresistive force sensing	Force / pressure	Glove-proof under-trim sensing concept; direct grip-force proxy; easy to segment by grip zone	Drift, creep, temperature sensitivity, and force transfer variability through trim layers	Segmented FSR strips or pressure-sensitive zones under steering wheel cover for grip/contact detection	M3 — Mechanical force / Pressure / Strain		**C2 Merged**
R-006	Product / Technical article	Structural testing	Strain gauges for force, deformation, and load measurement	Resistance strain gauge sensing	Strain → force / deflection / torque proxy	Non-capacitive; robust to gloves/wet conditions; can be hidden in wheel structure	Small signals, temperature drift, adhesive aging, and sensitivity to hand location / structural design	Strain gauges embedded in steering wheel rim or spokes to infer grip-induced deformation or steering interaction	M3 — Mechanical force / Pressure / Strain		**C3 Kept as standalone candidate**
R-007	Product	Industrial HMI	IR shadow-triangulation touch/hover sensing on framed display surfaces	Optical IR shadow-based sensing	Touch / hover	Interesting non-capacitive optical principle; offers proximity/hover-style channel	Poor transferability to 3D curved, soft steering wheel geometry; requires perimeter frame and planar interaction surface	Potentially only a weak inspiration for optical proximity ideas; not a strong direct steering wheel concept	M5 — Optical / Vision-based		**Reference / fusion inspiration Excluded**
R-008	Product	Aviation Safety	Deadman handle requiring continuous operator hold during refuelling operations	Electromechanical switch / continuous-hold interlock	Intentional continuous hold / operator engagement	Strong safety logic precedent; simple and proven enforcement mechanism	Not really a sensing modality for distributed hand detection; transfer to steering wheel raises fatigue, bypass, and usability concerns	More relevant as an HMI/safety-interlock logic reference than as a direct steering wheel sensing concept	M3 — Mechanical force / Pressure / Strain		**Reference / fusion inspiration Excluded**
L-01	Literature	Soft robotics	Fluid-channel elastomer skin using contact-induced hydraulic resistance change, with optional fluid-based thermal control	Fluid-pressure sensing through embedded deformable channels; optional thermo-enabled architecture	Contact-induced pressure rise; optionally thermal state	No discrete sensor on outer touch surface; can combine contact sensing with warm-surface functionality; flexible skin-like architecture	High system complexity: pump, tank, channels, pressure sensor; leak/durability risk; weak localization unless segmented; flow-control coupling can affect detection	Embedded fluid-channel steering wheel skin where grip/contact compresses channels and raises measured loop pressure for hands-on/off detection	M3 — Mechanical force / Pressure / Strain		**C4 Merged**
L-02	Literature	Robotics	Multimodal taxel skin combining fabric-based force sensing and thermistors in passive/active thermal modes	Force sensing plus thermal sensing in repeated taxels	Contact force; thermal response / contact-related thermal transient	Direct contact evidence from force channel; thermal cue can improve robustness; modular taxels can support zonal sensing	Thermal response is slower than force; active thermal adds power/control/safety burden; taxel density may affect packaging and grip feel	Force-dominant multimodal taxel skin around steering wheel rim, using force threshold as primary HOD signal and thermal as optional confirmation	M3 — Mechanical force / Pressure / Strain		**C2 Merged**
L-03	Literature	Automotive	In-cabin camera hand detection and hand-wheel interaction inference using hand detection, wheel region identification, and temporal tracking	Optical vision-based hand detection with spatial hand–wheel association and tracking	Hand presence on/near wheel; optional hand position / 0-1-2 hands on wheel	Non-contact; no wheel hardware modification; explicit hand-wheel overlap logic; temporal tracking improves stability	Sensitive to occlusion, illumination, viewpoint variation, and partial visibility; contact is inferred visually rather than directly measured	In-cabin camera system observing steering wheel region and classifying hands-on/off from hand–wheel spatial relationship over time	M5 — Optical / Vision-based		**C5 Merged**
L-04	Literature	Acoustic sensing	Airborne ultrasonic hand/gesture sensing using echo or Doppler signatures, with phased array, MEMS transducer cluster, or speaker-microphone variants	Ultrasonic / acoustic active sensing using echoes or Doppler patterns	Hand presence / motion patterns in sensing zone	Non-camera and non-contact; multiple architecture options; can support spatial processing or low-compute variants depending on implementation	Not validated directly for steering wheel hands-on truth; air attenuation, reflections, beam artifacts, and acoustic integration challenges	Ultrasonic sensing aimed at steering wheel region to detect whether hands are present near/on the wheel based on echo or Doppler evidence	M6 — Ultrasonic / Acoustic		**C7 Kept as standalone candidate**
L-05	Literature	Automotive	In-cabin radar hand/gesture recognition using FMCW range-angle/range-Doppler processing or IR-UWB feature extraction	Radar / mmWave or IR-UWB active sensing	Hand-related radar returns in predefined interaction zone	Works without lighting; lower privacy concerns than camera; supports both high-capability and lower-compute implementation paths	Evidence is still gesture-recognition-based rather than direct wheel-contact truth; clutter/interference and close-range interpretation remain challenges	Radar sensing of a predefined steering wheel interaction zone to infer hands-on/off from persistent hand-like returns	M7 — Radar / mmWave		**C8 Merged**
L-06	Literature	Medical	MRI-compatible grip-force sensor designed to measure human hand-grip force during neuroscience and fMRI experiments.	Intensity-based fiber-optic distance sensing	Displacement between the fiber head and mirror then converted into grip force (N)	Fully MRI-compatible (non-electrical, non-metallic at the sensor site); Low cost, fast to manufacture, customizable via hinge thickness; High linearity and accuracy in 0–500 N force range; Fast response suitable for rapidly	PLA material creep causes drift during long-term loading; Nonlinearity increases above 500 N; Temperature-dependent behavior of PLA; Requires precise fiber-mirror alignment; Not designed for broad contact areas or distributed sensing	This sensing concept detects force-induced deformation, not simple touch. Therefore, it would only sense grip pressure, not hands-on presence without force. The compliant structure mechanism is not naturally	M5 — Optical / Vision-based	NA	**C6 Merged**
L-07	Literature	Robotics	Instrumenting a single silicone pillar from the PapillArray tactile sensor using an optical pinhole-camera method. The pillar acts like an artificial skin papilla that can detect force, displacement, and incipient	Pinhole camera–based optical sensing	3D Dislacement, 3D Force, Vibration, Incipient slip indicators	Very high sensitivity: micron-level displacement accuracy & sub-millinewton force resolution; Detects high-frequency vibrations up to 1000 Hz, similar to human touch; Measures true 3D force + 3D	Accuracy decreases when the pillar is pressed at non-planar or angled contact surfaces; Silicone material is soft and prone to wear, may need protective coatings; Requires precise alignment of reflector, pinhole, and photodiode; Sensitive to external vibrations,	Very poor suitability. The sensor is designed for fine tactile robotic manipulation — not for large, durable, automotive steering wheels. It is too vibration-sensitive, too delicate, not durable under	M5 — Optical / Vision-based; M3 — Mechanical force / Pressure / Strain	NA	**Reference / fusion inspiration Excluded**
L-08	Literature	Robotics	High-speed tactile sensor designed for robot hands to detect incipient slip during grasping and manipulation. It focuses on recognizing early slip vibrations so robots can adjust grip force	Piezo-resistive tactile sensing	Local pressure/force distribution on the tactel grid; High-frequency slip vibrations	Very high frame rate (up to 1.9 kHz) for fast slip detection; Good spatial resolution (5 mm); Modular and scalable sensor design; High sensitivity to low forces (first-touch detection)	Designed for robot fingertips, not large surfaces; Sensitive to environmental factors (wear, humidity, noise); Requires complex signal processing + ML; Limited robustness for automotive conditions	Not suitable as a direct HOH solution; the sensor is over-engineered, environmentally fragile, and not optimized for large curved surfaces. Could theoretically detect	M3 — Mechanical force / Pressure / Strain	ML	**C2 Merged**
L-09	Literature	Automotive	Three vehicles of the same model have different hands-off detection performance because their steering mechanical loads differ, especially Vehicle #2, which has higher Power-Off	Torque-difference–based detection	Torque sensor value, steering angle, yaw rate, vehicle speed, steering assist torque, lane geometry from front camera, steering wheel angular	High accuracy (LSTM ~99%), robust across vehicles, enhanced rule-based method improves accuracy without extra hardware, uses existing signals only.	Rule-based method inconsistent across vehicles; threshold tuning is unstable; LSTM cannot run on current MCU due to memory limits; depends on correct mechanical parameters.	NA	M3 — Mechanical force / Pressure / Strain	ML/DL	**C9 Merged**
L-10	Literature	Robotics	A padded robot arm equipped with the multi-layer tactile sensing skin is used as the example to distinguish light touches (like a finger press) from strong impacts (like a	Piezoresistive sensing (resistance change under strain) + Electrical Impedance Tomography (EIT) for conductivity/impedance mapping	Touch force level, touch modality (press, tap, punch, pinch, slide, rub), and spatial touch patterns (single-point, multi-point, sliding).	High sensitivity to light touch, extended force range, multi-touch & modality detection, and flexible large-area coverage.	Hysteresis/memory effects, signal scatter for strong human touches, baseline drift from foam, and limited sliding detection with strip sensors.	Not evaluated for automotive use: no environmental, durability, or vibration testing—thus not directly transferable to steering-wheel HOD	M3 — Mechanical force / Pressure / Strain; M2. Impedance / Bio-impedance / Galvanic coupling	NA	**C10 Merged**
L-11	Literature		A fabric-based multimodal capacitive sensor that detects pressure, hand proximity, and magnetic fields using magnetic tilted micropillars.	Capacitive sensing (plate capacitance + fringe capacitance changes).	Pressure Proximity (hand) Magnetic field	High sensitivity, fast response, multimodal detection, clear discrimination between stimuli, flexible fabric-based structure.	No environmental testing; no heat/sweat/UV/friction durability; no automotive validation; only 5000-cycle mechanical testing	Conceptually flexible enough to wrap surfaces, but not validated for automotive, vibration, heat, sweat, or long-term wear.	M1 — Electric-field / Capacitive	NA	**C1 Merged**
L-12	Literature		A dual-mode capacitive sensor is demonstrated for touchless gesture and tactile pressing control of a robotic arm.	Capacitive sensing using fringe electric field for proximity + dielectric deformation for pressure.	Distance (proximity) and pressure (tactile force).	High proximity range (110 mm), high low-pressure sensitivity, clear separation of touchless vs tactile signals, excellent repeatability.	No environmental tests (heat, humidity, sweat), no automotive robustness info, fabrication complexity.	Not evaluated for curved surfaces or automotive conditions.	M1 — Electric-field / Capacitive	NA	**C1 Merged**
L-13	Literature	Robotics	A modular proximity + contact sensor array is mounted on a human-cooperative robot arm to detect approaching objects and	Time-of-Flight (optical distance measurement) + Self-capacitance sensing (capacitance change with object presence/contact).	Distance (ToF); Close-range approach (capacitance); Contact/touch (capacitance); Object	Seamless detection from 300 mm → contact; High close-range sensitivity; Modular and expandable; Detects both proximity and touch	ToF inaccurate <10 mm; Capacitance depends on object material/size; Curved surfaces cause blind spots; Cannot detect pressure	Not designed for steering wheels; rigid modules, IR sensitivity, and environmental limitations make direct translation unsuitable.	M1 — Electric-field / Capacitive; M5 — Optical / Vision-based	NA	**Reference / fusion inspiration Excluded**
L-14	Literature		A capacitive sensor made using nanostructured fibrous electrodes for detecting hand proximity, finger force, and water mass.	Capacitive sensing using ΔC = $C_1 - C_0$ with nanostructured (CNT–cellulose) electrodes to enhance electric-field	Hand proximity, finger force/pressure, water mass, and hand gestures (via ML).	High sensitivity, long detection range (up to 300 mm), small form factor, dual detection (proximity + force), and low variation (<0.4%).	Performance drops in conductive environments; no data on durability, environmental robustness, or automotive-grade conditions.		M1 — Electric-field / Capacitive	ML	**C1 Merged**
L-15	Literature	Industrial HMI	Screen-printed IDC sensors used for pressure-sensitive HMIs (RGB control, keyboard input, gaming) and breathing monitoring via	Interdigitated capacitive sensing based on changes in fringing electric-field capacitance due to pressure or humidity.	Pressure, capacitance change, humidity, and breathing moisture patterns.	Low-cost, flexible, fast response (11–15 ms), multi-mode sensing (pressure + humidity + breathing), durable over 20,000 cycles.	No automotive-grade testing; no validation for UV, sweat, friction, vibration, or wide temperature range; limited to flat PET substrates.	Would require major redesign for curvature, environmental durability, and EMC/ESD robustness	M1 — Electric-field / Capacitive	NA	**C1 Merged**
L-16	Literature		Curved, clamped PVDF-film contact vibration sensor used for stethoscope/contact microphone applications.	Piezoelectric PVDF film converting mechanical vibration pressure → planar strain → electric charge/voltage.	Mechanical vibration, acoustic pressure, body-surface vibration, solid-surface vibration.	High sensitivity (~1.5 mV/Pa), flat response up to ~4 kHz, detects low-frequency body vibrations, low-cost thin film.	Resonance at ~6 kHz; requires rubber interface; affected by external mechanical noise; no environmental robustness discussed.	Detects hand-induced vibrations on wheel surface via curved PVDF film if mechanically coupled.	M3 — Mechanical force / Pressure / Strain	NA	**C10 Kept as standalone candidate**
L-17	Literature	Research	Deformable musical instrument; soft numeric keypad; activity-sensible cushion.	Swept-Frequency Capacitive Sensing (SFCS) / multi-frequency impedance sensing applied to conductive foam with a single wire.	The directly measured variable is impedance response across multiple frequencies. From that, the system infers gesture type	Multimodal gesture sensing with very simple hardware (single wire, soft conductive foam); strong lab classification performance with mesh shield.	No evidence for automotive robustness, durability, EMC/ESD, or environmental tolerance; mainly a lab prototype.	Promising for proof-of-concept on a wheel segment or mockup; not proven for full automotive production use.	M3 — Mechanical force / Pressure / Strain; M2. Impedance / Bio-impedance	ML	

	Concepts									
Selection Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
	(Reference)Distributed capacitive sensing layer	Distributed pressure sensing layer	Structural strain / rim deformation sensing	Microfluid grip-sensing	Cabin camera hand-wheel interaction sensing	Embedded optical grip sensing	Ultrasonic wheel-zone hand presence sensing	Radar / mmWave wheel-zone hand presence sensing	Steering-torque-based sensing	Single-wire conductive foam grip sensing
1. Functional relevance to HOD	0	+	+	-	-	0	-	-	-	0
2. Output stability and decision support	0	0	0	0	-	+	-	-	-	0
3. Robustness to user and environmental variation	0	+	+	+	+	+	0	+	+	+
4. Integration and transfer feasibility	0	0	-	-	+	-	+	+	0	0
5. Evidence maturity and credibility	0	0	-	-	+	-	0	0	0	-
6. Development and validation burden	0	0	0	-	+	-	+	+	0	0
7. Fusion complementarity potential	0	0	0	0	+	0	+	+	0	0
Sum +	0	2	2	1	5	2	3	4	1	1
Sum 0	7	5	3	2	0	2	2	1	4	4
Sum -	0	0	2	4	2	3	2	2	2	1
Net Score	0	2	0	-3	3	-1	1	2	-1	0
Rank	4	2	4	6	1	5	3	2	5	4
Continue?	Yes	Yes	Yes	No	Yes	No	Replaced by radar (C8)	Yes	Yes	Yes

Architecture rules
1. Does it include at least one direct-contact or contact-related concept?
2. Does it include complementary sensing logic?
3. Is the combined architecture conceptually integrable?
4. Is it too redundant or too overloaded?

No.	Combination	Architecture Check	Comment
1	C1 + C2 + C3	Pass	
2	C1 + C2 + C4	Pass	
3	C1 + C2 + C5	Pass	
4	C1 + C2 + C6	Pass	
5	C1 + C2 + C7	Pass	
6	C1 + C3 + C4	Pass	
7	C1 + C3 + C5	Pass	
8	C1 + C3 + C6	Pass	
9	C1 + C3 + C7	Pass	
10	C1 + C4 + C5	Not Pass	too redundant
11	C1 + C4 + C6	Pass	
12	C1 + C4 + C7	Pass	
13	C1 + C5 + C6	Pass	
14	C1 + C5 + C7	Pass	
15	C1 + C6 + C7	Pass	
16	C2 + C3 + C4	Pass	
17	C2 + C3 + C5	Pass	
18	C2 + C3 + C6	Not Pass	too redundant
19	C2 + C3 + C7	Not Pass	too redundant
20	C2 + C4 + C5	Not Pass	too redundant
21	C2 + C4 + C6	Pass	
22	C2 + C4 + C7	Pass	
23	C2 + C5 + C6	Pass	
24	C2 + C5 + C7	Pass	
25	C2 + C6 + C7	Not Pass	too redundant
26	C3 + C4 + C5	Not Pass	too redundant
27	C3 + C4 + C6	Pass	
28	C3 + C4 + C7	Not Pass	too redundant
29	C3 + C5 + C6	Pass	
30	C3 + C5 + C7	Pass	
31	C3 + C6 + C7	Not Pass	too redundant
32	C4 + C5 + C6	Not Pass	too redundant
33	C4 + C5 + C7	Not Pass	too redundant
34	C4 + C6 + C7	Pass	
35	C5 + C6 + C7	Pass	

Selection Criteria	C1 + C2 + C3	C1 + C2 + C4	C1 + C2 + C5	C1 + C2 + C6	C1 + C2 + C7	C1 + C3 + C4	C1 + C3 + C5	C1 + C3 + C6	C1 + C3 + C7	C1 + C4 + C7	C1 + C4 + C6	C1 + C5 + C6	C1 + C5 + C7
1. Complementarity of sensing evidence	0	+	+	+	0	+	+	+	0	+	+	+	+
2. Expected robustness through redundancy	0	0	0	0	0	0	0	0	0	0	+	-	0
3. System integration feasibility	0	+	+	+	0	+	+	+	0	+	+	+	+
4. System complexity / calibration burden	0	0	0	0	0	0	0	+	+	0	-	-	-
5. Value for HO / HOF / Uncertain classification	0	+	+	0	0	+	+	0	0	+	+	+	+
Sum +	0	3	3	2	0	3	3	3	1	3	4	3	3
Sum 0	5	1	2	3	5	2	2	2	4	1	0	0	1
Sum -	0	1	0	0	0	1	1	0	0	1	1	2	1
Net Score	0	4	4	3	0	3	3	3	1	4	3	1	2
Rank	4	1	1	2	4	2	2	2	4	1	2	4	3
Continue?	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	No	No

Selection Criteria	C1 + C6 + C7	C2 + C3 + C4	C2 + C3 + C5	C2 + C4 + C6	C2 + C4 + C7	C2 + C5 + C6	C2 + C5 + C7	C3 + C4 + C6	C3 + C5 + C6	C3 + C5 + C7	C4 + C6 + C7	C5 + C6 + C7
1. Complementarity of sensing evidence	+	0	0	+	0	+	0	+	+	0	+	+
2. Expected robustness through redundancy	+	0	0	0	0	0	0	0	0	0	0	0
3. System integration feasibility	0	0	0	+	0	0	0	+	+	0	+	+
4. System complexity / calibration burden	+	+	+	+	+	+	+	+	+	+	+	+
5. Value for HO / HOF / Uncertain classification	0	+	+	+	+	+	+	+	+	+	+	+
Sum +	3	2	2	4	2	3	2	4	4	2	4	4
Sum 0	2	3	3	1	3	2	3	1	1	3	1	1
Sum -	0	0	0	0	0	0	0	0	0	0	0	0
Net Score	3	2	2	4	2	3	2	4	4	2	4	4
Rank	2	3	3	1	3	2	3	1	1	3	1	1
Continue?	Yes	No	No	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes

C1 = Capacitive sensing
C2 = Resistive sensing
C3 = Strain fabric
C4 = Cabin camera
C5 = mmRadar
C6 = Torque sensor
C7 = Foamin multimodal sensing

C1 + C2 + C4
C1 + C2 + C5
C1 + C2 + C6
C1 + C3 + C4
C1 + C3 + C5
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C1 + C4 + C7
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C5 + C6 + C7

Focus on this

C1 + C3 + C4
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C1 + C6 + C7

C3 + C4 + C6
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		Concepts																			
		C1 + C3 + C4		C1 + C3 + C5		C1 + C3 + C6		C1 + C4 + C6		C1 + C4 + C7		C1 + C6 + C7		C3 + C4 + C6		C3 + C5 + C6		C4 + C6 + C7		C5 + C6 + C7	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
1. Detection performance	**25%**	4	1	4	1	4	1	4	1	5	1.25	5	1.25	3	0.75	3	0.75	4	1	4	1
2. Robustness to disturbances	**20%**	3	0.6	3	0.6	3	0.6	4	0.8	4	0.8	4	0.8	4	0.8	4	0.8	5	1	5	1
3. Dynamic decision quality	**15%**	4	0.6	4	0.6	4	0.6	3	0.45	3	0.45	4	0.6	4	0.6	4	0.6	4	0.6	3	0.45
4. Fusion complementarity & redundancy benefit	**15%**	5	0.75	5	0.75	3	0.45	5	0.75	4	0.6	4	0.6	4	0.6	4	0.6	4	0.6	4	0.6
5. Engineering integration feasibility	**15%**	4	0.6	4	0.6	4	0.6	5	0.75	4	0.6	4	0.6	5	0.75	5	0.75	5	0.75	5	0.75
6. System complexity & resource burden	**7%**	2	0.14	2	0.14	4	0.28	3	0.21	3	0.21	4	0.28	3	0.21	2	0.14	4	0.28	3	0.21
7. Industrialization feasibility	**3%**	3	0.09	3	0.09	3	0.09	5	0.15	3	0.09	3	0.09	3	0.09	3	0.09	3	0.09	3	0.09
Total Score		3.78		3.78		3.62		4.11		4		4.22		3.8		3.73		4.32		4.1	
Rank		7		7		9		3		5		2		6		8		1		4	
Continue?								Pass				Pass						Pass			

C1	C2	C3	C4	C5	C6	C7
(Reference) Distributed capacitive sensing layer	Distributed pressure sensing layer	Structural strain / rim deformation sensing	Cabin camera hand-wheel interaction sensing	Radar / mmWave wheel-zone hand presence sensing	Steering-torque-based sensing	Conductive foam grip sensing

B

Selected Literature for Concept Extraction

Table B.1: Selected literature used for concept extraction

Modality	**First author**	**Year**	**Title**
M1 Capacitive	Choi	2020	Transparent Pressure Sensor with High Linearity over a Wide Pressure Range for 3D Touch Screen Applications
M1 Capacitive	Hsu	2024	A Capacitive Sensor Readout IC With Antenna-Integrated Sensor for Proximity Detection in Handheld Mobile Devices
M1 Capacitive	Li	2022	Ultrasensitive Capacitive Sensor Composed of Nanostructured Electrodes for Human–Machine Interface
M1 Capacitive	Liu	2024	A Flexible Dual-Mode Capacitive Sensor for Highly Sensitive Touchless and Tactile Sensing in Human–Machine Interactions
M1 Capacitive	Nisar	2025	Screen Printed Flexible IDC Sensors for Pressure Sensitive HMIs and Breathing Applications
M1 Capacitive	Song	2025	A Fabric-Based Multimodal Flexible Tactile Sensor With Precise Sensing and Discrimination Capabilities for Pressure–Proximity–Magnetic Field Signals
M1 Capacitive	Tsuji	2020	Proximity and Contact Sensor for Human Cooperative Robot by Combining Time-of-Flight and Self-Capacitance Sensors
M1 Capacitive	Wang	2020	A Dual-Trigger-Mode Ionic Hydrogel Sensor for Contact or Contactless Motion Recognition
M2 Impedance	Chen	2018	Compliant Multi-Layer Tactile Sensing for Enhanced Identification of Human Touch
M3 Mechanical	Bützer	2016	Design and Evaluation of a Fiber-Optic Grip Force Sensor with Compliant 3D-Printable Structure for (f)MRI Applications

Continued on next page

Modality	**First author**	**Year**	**Title**
M3 Mechanical	Khamis	2019	A Novel Optical 3D Force and Displacement Sensor – Towards Instrumenting the PapillArray Tactile Sensor
M3 Mechanical	Kim	2025	Enhancing Rule-Based Hands-Off Detection With Deep Learning and Permutation Feature Analysis
M3 Mechanical	Schürmann	2012	A High-Speed Tactile Sensor for Slip Detection
M4 Thermal	Shionoiri	2025	Fluid-Based Robot Skin for Contact Detection and Thermal Stimulation
M4 Thermal	Wade	2017	A Force and Thermal Sensing Skin for Robots in Human Environments
M5 Optical	Borghi	2018	Hands on the Wheel: A Dataset for Driver Hand Detection and Tracking
M5 Optical	Das	2015	On Performance Evaluation of Driver Hand Detection Algorithms: Challenges, Dataset, and Metrics
M5 Optical	Le	2016	Multiple Scale Faster-RCNN Approach to Driver's Cell-Phone Usage and Hands on Steering Wheel Detection
M5 Optical	Rangesh	2016	Long-Term Multi-Cue Tracking of Hands in Vehicles
M6 Ultrasonic	Fertl	2024	End-to-End Ultrasonic Hand Gesture Recognition
M6 Ultrasonic	Ibrahim	2020	Low Complexity Multi-Directional In-Air Ultrasonic Gesture Recognition Using a TCN
M6 Ultrasonic	Li	2024	Design and Implementation of a FPGA-Based Airborne Ultrasound Sensing and Radiation Phased Array Device
M7 Radar	Khan	2017	Hand-Based Gesture Recognition for Vehicular Applications Using IR-UWB Radar
M7 Radar	Wang	2022	Multi-Hand Gesture Recognition Using Automotive FMCW Radar Sensor

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