

Interference-Resilient AGV and Asset Tracking Using Tag-Based Harmonic Radar for Industrial Logistics

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Industrial logistics requires reliable localization of robots and tracking of assets in dynamic, cluttered, and metallic environments. Camera and light detection and ranging systems can lose robustness under changing visibility, occlusion, reflective structures, and limited geometric observability. Conventional radio localization is also affected by multipath propagation and metallic surroundings. This paper provides a technical overview of a novel tag-based harmonic radar system operating at 61/122 GHz in four logistics scenarios. These scenarios comprise high-dynamic operation of automated guided vehicles, parcel pick-up at a metallic station, small-load-carrier monitoring in shelves, and production asset tracking. A structured expert process applies common performance criteria to derive scenario-specific requirements and select suitable radar-tag topologies. The paper also discusses initial integration on two robot platforms: The RoboChief robot for parcel pick-up and the cable robot for shelf monitoring. The combined analysis and platform integrations establish a technical basis for systematic validation and robust deployment of harmonic-radar systems in industrial logistics.

[Keywords: industrial logistics, harmonic radar, automated guided vehicle localization, asset tracking, active tags]

Die industrielle Logistik erfordert eine zuverlässige Lokalisierung der Roboter und die Verfolgung von Objekten in dynamischen, unübersichtlichen und metallischen Umgebungen. Kamera- und lichtbasierte Entfernungsmesssysteme können bei wechselnden Sichtbedingungen, Verdeckungen, reflektierenden Strukturen und geringer geometrischer Beobachtbarkeit an Robustheit verlieren. Konventionelle funkbasierte Lokalisierung wird zudem durch Mehrwegeausbreitung und metallische Umgebungen beeinträchtigt. Dieser Beitrag bietet einen technischen Überblick über ein neuartiges tagbasiertes harmonisches Radarsystem bei 61/122 GHz in vier Logistik-szenarien. Diese Szenarien umfassen den dynamischen Betrieb fahrerloser Transportfahrzeuge, die Paketauf-

nahme an einer metallischen Station, Überwachung von Kleinladungsträgern in Regalen und Objektverfolgung in der Produktion. Ein strukturierter Expertenprozess wendet gemeinsame Leistungskriterien an, um szenariospezifische Anforderungen abzuleiten und geeignete Radar-Tag-Topologien auszuwählen. Zudem wird die erste Integration auf zwei Roboterplattformen diskutiert: dem RoboChief für die Paketaufnahme und dem Seilroboter für die Regalüberwachung. Die kombinierte Analyse und die Plattformintegrationen schaffen eine technische Grundlage für die systematische Validierung und robuste Umsetzung harmonischer Radarsysteme in der industriellen Logistik.

[Schlüsselwörter: Industrielogistik, harmonisches Radar, Lokalisierung fahrerloser Transportfahrzeuge, KLT-Verfolgung, aktive Tags]

1 INTRODUCTION

High-throughput logistics systems require precise localization of fleets of automated guided vehicles (AGVs) and reliable tracking of assets such as small load carriers (SLCs) in dynamic, cluttered, and metallic environments. Localization provides the state information needed to coordinate material flows and connect physical movements with digital process states. For AGVs, it supports navigation, collision avoidance, docking, and transfer operations. For tracked assets, it supports inventory visibility, storage-position verification, and process monitoring. Highly dynamic automated guided vehicle (AGV) platforms such as LoadRunner® illustrate the potential of distributed, cooperative transport systems, but they also increase the demand for low-latency and dependable state information for safe and efficient material-flow control [1].

Industrial halls present challenging conditions for these functions. Metal shelves, machines, load carriers, gates, and vehicles create reflections, occlusions, and locally restricted fields of view. Camera-based localization provides rich visual and semantic information, but it depends on sufficient

illumination and observable, unoccluded features [2, 3]. Light detection and ranging (LiDAR) measures geometry largely independently of illumination, yet repetitive layouts, partial views, and limited geometric diversity can weaken scan-matching observability [4]. Radio localization based on received signal strength is affected by multipath, non-line-of-sight propagation, interference, and device orientation [5]. Together, these limitations motivate complementary sensing methods for reliable localization and tracking in demanding industrial logistics processes and automated material flows under realistic operating conditions.

A novel tag-based harmonic radar system operating at 61/122 GHz applies a cooperative sensing principle. The radar transmits a signal near 61 GHz toward designated active harmonic tags. The tags convert the received signal and retransmit a nonlinear response near 122 GHz. Localization thus depends on interaction between the radar sensor and specifically marked objects rather than solely on passive reflections from the surrounding environment. Most surrounding structures respond linearly at the transmitted frequency. Consequently, harmonic-band reception suppresses much of this linear clutter [6]. The multi-target system assigns a distinct modulation frequency to each tag. It can consequently identify and range several tags within the same chirp and use them as distinguishable landmarks for multilateration [7]. This spectral and identity selectivity provides a technically distinct sensing channel but cannot eliminate geometric occlusion, multipath propagation, or nonlinear interference within the operating environment.

This paper addresses the following research question: *How should tag-based harmonic radar be configured for reliable localization and tracking across industrial logistics scenarios?* Accordingly, the paper provides a technical overview of the sensing approach in four logistics scenarios. It derives scenario-specific requirements and maps the resulting profiles to suitable radar-tag topologies. It also discusses the first system integrations on two robot platforms: a radar mounted on the RoboChief AGV for parcel pick-up and cable-robot-assisted sensor positioning for shelf monitoring. Throughout the paper, target requirements and proposed concepts are clearly distinguished from implemented setups and experimentally validated performance to indicate the current level of technical maturity for each scenario and integration path considered in the requirement analysis.

2 RELATED WORK

2.1 AGV LOCALIZATION IN INDUSTRIAL LOGISTICS

Modern AGVs combine wheel odometry and inertial sensing with sensors that observe the surrounding environment. Camera-based localization and visual simultaneous localization and mapping (SLAM) provide rich geometric

and semantic information. In intralogistics, semantic mapping associates detected objects and operational areas with an AGV map [8]. More generally, semantic visual mapping combines camera-based pose estimation with object and scene interpretation [3]. Its performance depends on visible features, adequate illumination, camera calibration, and limited occlusion or scene change during operation. The LoadRunner® platform illustrates this approach in highly dynamic transport by using an AGV-mounted high-speed camera and graphics-processing hardware to estimate position from the floor structure [1].

LiDAR measures geometric structure largely independently of illumination. Reflective surfaces, partial views, and repetitive geometry can nevertheless weaken scan association in confined stations or shelf aisles [4]. Learning-based mapping and object interpretation can improve scene understanding, but they cannot replace reliable sensor observations [9]. Camera and ranging systems therefore remain strong general-purpose solutions, while complementary landmarks can support precise docking and recovery from poor geometric observability in confined workspaces.

2.2 RADIO-BASED LOCALIZATION AND ASSET TRACKING

Radio technologies such as ultra-wideband (UWB), radio-frequency identification (RFID), Bluetooth, and wireless local-area networks support indoor positioning and asset monitoring. They infer position from time of flight, time differences, received signal strength, angle, fingerprints, or proximity events. Their accuracy and availability depend on bandwidth, synchronization, anchor geometry, non-line-of-sight propagation, and environmental calibration [5]. A grid-based *Sensor Floor* [10] illustrates this approach by combining dual-band radio and inertial measurements with machine-learning-based robot localization, for which an accuracy of approximately 0.15 m was reported. Multipath in metallic warehouses complicates tag detection near shelves and machines. This limitation motivates selective markers that remain distinguishable from linear clutter.

2.3 HARMONIC RADAR AND THE LOGISTICS RESEARCH GAP

Harmonic radar marks a target with a nonlinear transponder. At millimeter-wave frequencies, engineered harmonic tags can be assumed to dominate the significant nonlinear radar response in the intended scene. Consequently, predefined navigation waypoints can be marked with tags that have unique modulation characteristics [7]. Compact active tags and a frequency-doubling architecture at 61/122 GHz have demonstrated precise ranging with reduced linear clutter [6, 7]. A distributed sensor network has also demonstrated three-dimensional tag localization by

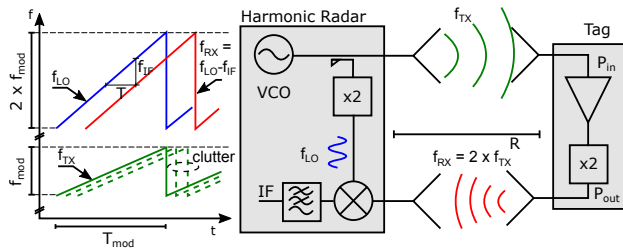


Figure 1: Operating principle of the 61/122 GHz harmonic FMCW radar with transmission at f_0 and reception of the frequency-doubled tag response at $2f_0$ in the harmonic band. This spectral separation suppresses linear clutter.

multilateration using calibrated sensor positions [11]. Tag modulation further supports identification, status reporting, and joint communication and sensing functions [12]. These studies establish technical feasibility but do not determine an appropriate logistics deployment. AGV localization, station alignment, shelf monitoring, and production tracking impose different constraints. The research gap is therefore not another microwave circuit or localization estimator. It is a transfer method that links logistics requirements to radar-tag topology, mechanical integration, data interfaces, and infrastructure planning for deployment.

3 TECHNICAL BACKGROUND: TAG-BASED HARMONIC RADAR

3.1 OPERATING PRINCIPLE

Figure 1 illustrates the operating principle of the investigated harmonic radar. The radar transmits a frequency-modulated continuous-wave (FMCW) signal at a fundamental frequency f_0 in the 61 GHz band. An active tag converts the incident signal and retransmits it near $2f_0$ in the 122 GHz band. The harmonic-radar receiver mixes this response with the corresponding local-oscillator signal to form an intermediate-frequency beat signal whose frequency contains the target-range information. Depending on the waveform and processing configuration, this signal can also provide radial velocity. Angular information is obtained from multi-channel realizations that evaluate phase differences between spatially separated receive channels [6, 13]. Multiple radar sensors can combine range observations through multilateration to estimate a three-dimensional tag position when their positions are calibrated and their timing relationships are consistent [11].

Shelves, machines, walls, and vehicles primarily return linear reflections at f_0 , whereas the tag deliberately generates a response at $2f_0$. Reception near 122 GHz therefore separates the tag response from conventional reflections at the transmitted frequency and suppresses much of the linear clutter. It does not eliminate all disturbances because non-linear components, parasitic emissions, multipath propaga-

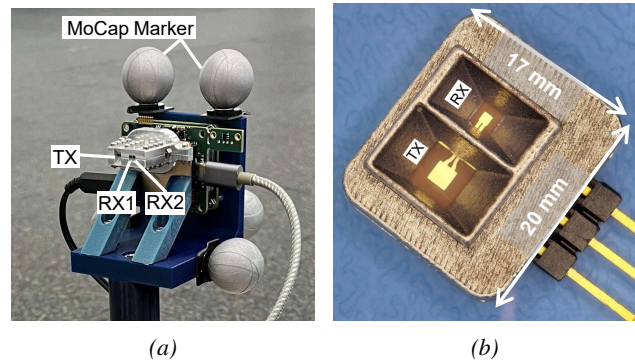


Figure 2: Hardware components of the tag-based harmonic radar system: (a) compact radar sensor with MoCap markers; and (b) active frequency-doubling tag in its metallic housing.

tion, occlusion, and interactions among multiple tags remain relevant. A further advantage of active tags is their ability to generate strong, well-resolved responses relative to interfering objects while retaining compact dimensions and low mass. In conventional linear radar systems, passive targets with comparable detectability generally require larger and heavier corner reflectors [7].

3.2 ACTIVE TAGS AND SENSING FUNCTIONS

Figure 2 shows the compact harmonic radar sensor with motion capture (MoCap) markers and the active harmonic tag in its metallic housing. The radar system measures approximately $40 \times 50 \times 43 \text{ mm}^3$ excluding the antenna [13]. The tag integrates receive and transmit antennas with a nonlinear frequency-doubling monolithic microwave integrated circuit (MMIC) on a compact printed circuit board (PCB) inside a metallic housing with lateral dimensions of $20 \times 17 \text{ mm}$ [7]. This compact implementation permits attachment to an AGV, small load carrier, tugger-train trailer, or fixed station landmark. The active architecture also permits modulation of the returned signal. This capability is available if the tag is combined with digital baseband circuitry. Initial work uses on-off keying to transfer information from the tag to the reader [12]. The forthcoming multi-target study uses tag-specific modulation for identification and data association [7]. The logistics integrations examined in the present paper do not assume an available industrial communication protocol.

3.3 GENERIC RADAR-TAG TOPOLOGIES

Assigning mobility either to the radar or to the tags yields two generic topologies for industrial logistics, both illustrated by the scenario concepts in Figure 3. *Mobile radar with stationary tags*: The radar is mounted on the AGV. Tags form known landmarks in the operating area or at a process station. This topology provides AGV-relative ob-

servations and limits infrastructure complexity. The observations support localization for navigation and route execution, including pose correction and precise station-relative alignment. *Infrastructure radar with mobile tags*: One or more radars are fixed or temporarily placed around a monitored area. Tags are attached to load carriers, assets, or AGVs. This topology moves the sensing hardware into the infrastructure. It supports process-level visibility across a shelf, workstation, or production zone. Coverage and identification are central design variables for deployment planning. A hybrid deployment is also possible. However, each scenario is first mapped to its simpler, dominant topology. The sensing principle remains unchanged. Radar placement, tag placement, density, and processing are adapted to the process requirements and operating environment.

4 RESEARCH METHODOLOGY AND INDUSTRIAL LOGISTICS SCENARIO DEFINITION

This section explains how the requirements are elicited for the four considered industrial logistics scenarios. Figure 3 summarizes overall scenario definitions and the proposed radar-tag topologies. The illustrated arrangements are in the conceptual phase. The harmonic radar topology and placement are later derived in Subsection 5.2 from the scenario-specific requirement profiles. We also introduce the experimental test infrastructure and the robot platforms.

4.1 REQUIREMENTS ELICITATION METHOD

The scenario requirements are elicited through a structured expert process involving project partners from research institutions, universities, and industries. The contributors represent logistics, robotics, radar engineering, and localization and production industries. This interdisciplinary composition connects operational process knowledge with the technical feasibility of the radar system. The analysis applies scenario-based requirements engineering because the required sensing performance depends on the logistics process, operating environment, and selected system topology [14]. The workflow follows established requirements-engineering principles by separating stakeholder needs, measurable system requirements, and verification criteria [15]. The experts discuss their assessments in a series of meetings. The process does not use anonymous Delphi rounds or statistical aggregation.

The contributors complete four traceable steps. First, logistics specialists specify the operational objective, monitored entity, process sequence, environmental conditions, and relevant failure consequences for each scenario. Second, the interdisciplinary group reviews each scenario using a common template. The template covers position and angle accuracy, update rate, operating range, resilience, sensor and tag mobility, interference, and scalability. Third,

the group converts qualitative needs into target values using process tolerances, AGV dynamics, station geometry, shelf layout, asset density, and the intended monitoring function. The experts then review the assumptions and technical feasibility of each profile. Finally, each requirement profile is mapped to a radar-tag topology and an integration path. This procedure produces traceable design targets for subsequent experiments. It does not claim statistical performance estimates or already achieved results.

4.2 INDUSTRIAL LOGISTICS SCENARIOS

The four scenarios cover complementary localization and tracking tasks in industrial logistics. Their operational processes and constraints provide the basis for the requirement profiles and topology mapping reported in Section 5.

4.2.1 SCENARIO 1 (S1): HIGHLY DYNAMIC AGV OPERATION FOR PARCEL SORTING

As shown in Figure 3a, a fleet of highly dynamic AGVs sorts parcels by transporting them from pick-up metallic stations to assigned drop-off stations. The AGVs follow predefined, time-dependent trajectories and operate cooperatively within a shared area. The origin, boundaries, and route definitions of this area are known. The localization output supports continuous trajectory execution and the supervision of deviations from planned motion. A one-time mapping or calibration phase is permissible when operation begins in a new environment. The AGVs can accelerate at up to 5 m/s^2 and reach approximately 10 m/s . The localization system therefore requires frequent position updates with low latency and limited jitter. It must remain available when several AGVs move simultaneously and temporarily obstruct individual lines of sight. Persistent trajectory deviations or prolonged invalid position data require a defined response from the supervisory control system.

4.2.2 SCENARIO 2 (S2): PARCEL PICK-UP AT A METALLIC STATION

As shown in Figure 3b, an AGV approaches a gate-shaped metallic station and collects a parcel using its load-handling mechanism. During passage, the mechanism must remain aligned with narrow station rails. The required lateral and angular tolerances are substantially tighter than during unconstrained travel. Insufficient station-relative accuracy currently limits the traversal speed. Comparable localization conditions occur when an AGV passes through gates, doors, airlocks, or other narrow metallic structures.

The station forms a tunnel-like environment around the AGV. Its metallic structure produces occlusion, reflections, and geometry-dependent multipath. The enclosure also re-

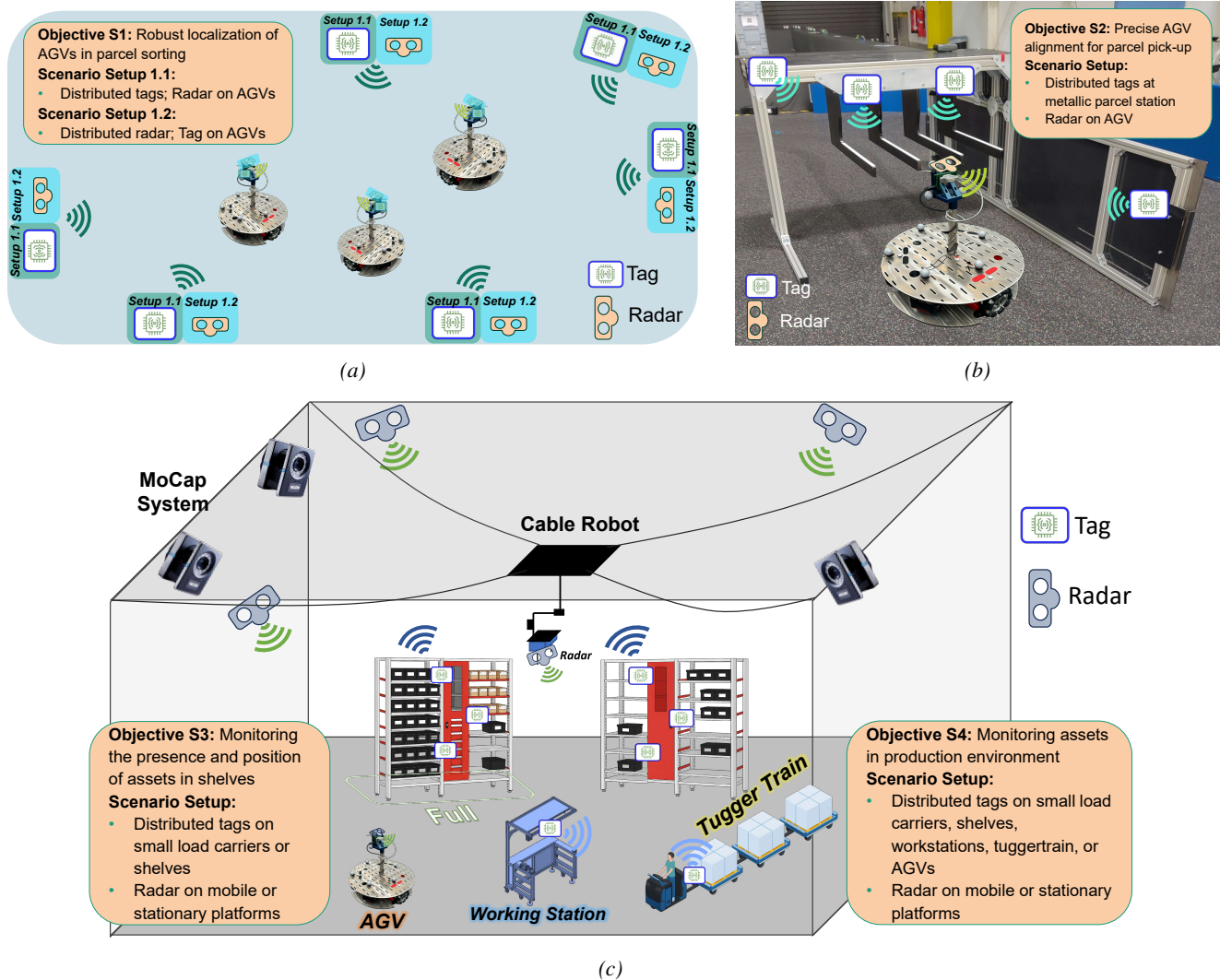


Figure 3: Four industrial logistics scenarios and the proposed harmonic radar topologies in this study: (a) Highly dynamic AGV operations for parcel sorting, (b) parcel pick-up at a metallic station, and (c) monitoring the position of assets in shelves and assets tracking in production environments.

stricts external camera visibility and causes abrupt illumination changes at the entrance and exit. Camera-based localization and external optical reference systems may consequently lose observability during passage. The AGV then depends more strongly on its Inertial Measurement Unit (IMU), although inertial errors accumulate without an external position correction inside the station.

4.2.3 SCENARIO 3 (S3): ASSET MONITORING IN SHELVES

As shown in Figure 3c, tagged assets or SLCs are monitored in metallic shelves and sorting stations. The process distinguishes whether a SLC has been inserted, removed, or placed in the intended shelf position. These observations

indicate arrival and completion events and may initiate replenishment after a SLC is removed. They can also update a digital inventory map with the current SLC identity and storage position. The inventory state changes slowly, but every event must be associated with the correct SLC and shelf location throughout the inventory cycle.

A dense arrangement of SLCs produces small spatial separations between neighboring tags. Shelf beams, adjacent containers, and metallic goods can obstruct the propagation path or generate strong reflections. These effects complicate tag identification and the assignment of observations to individual shelf positions. Sensor height, lateral offset, viewing angle, and distance determine which tags remain observable for different occupancy states. The final in-

stallation must therefore provide sufficient coverage without requiring an excessive number of infrastructure sensors.

4.2.4 SCENARIO 4 (S4): ASSET TRACKING IN PRODUCTION AREA

In the production-area scenario also shown in Figure 3c, assets or SLC are transported from a central store or warehouse entrance to production workstations. The process requires the route and current state of each SLC to remain observable. Alternatively, a tugger train may be tracked through a tag on the train or individual tags on its trailers. The observations support a comparison between completed and pending workstation visits. They also provide state information for later route adjustment when material-flow conditions change during operation. The production environment contains frequent occlusion and locally dense tag arrangements. Its total tag population and monitored area are also larger than in the shelf scenario. The system must preserve tag identity across overlapping coverage regions and associate each observation with the correct carrier, trailer, or process event. Addressing, data association, infrastructure density, and system integration therefore become central requirements for scalable deployment in complex and dynamic production environments.

4.3 EXPERIMENTAL TEST INFRASTRUCTURE

The analysis uses configurable indoor logistics laboratories and two complementary robot platforms. The facilities support controlled prototype development, while RoboChief and the cable robot provide AGV-mounted and infrastructure-planning experiments under reproducible laboratory conditions.

4.3.1 INDOOR LOGISTICS TEST FIELDS

The InnoLab at the Chair of Materials Handling and Warehousing (FLW) of TU Dortmund University [16] and the PACE Lab at Fraunhofer Institute for Material Flow and Logistics (IML) [17] provide configurable environments for prototype development and controlled evaluation. Together, the two facilities offer approximately 1,650 m² of indoor research space. Their halls reproduce realistic logistics conditions using high-bay shelves with reflective structures, transport systems, robot platforms, drones, and three-dimensional cable robots. A MoCap system provides precise reference poses for robots and other moving objects with sub-millimeter accuracy. These facilities support controlled system prototypes before transferred to industrial settings under realistic logistics conditions.

4.3.2 ROBOCHIEF AGV PLATFORM

RoboChief is a self-built, modular miniature of the LoadRunner® platform [1] intended for research on high-speed collaborative transport systems. The current platform has three omnidirectional wheels, a diameter of approximately 0.40 m, a height of 0.11 m, a payload of about 50 kg, and a maximum speed of 5 m/s. Larger variants with a diameter of approximately 0.80 m and higher payload capacities are under development. Modular interfaces support temporary integration of radar sensors, cameras, radio modules, manipulators, and custom software. Partner control algorithms can be evaluated while synchronized experimental data are recorded.

4.3.3 THREE-DIMENSIONAL CABLE ROBOT

The aerial cable robot executes accurate and repeatable three-dimensional trajectories within the research hall. A MoCap system supplies pose feedback for autonomous operation, while the cable-robot software retains control of all safety functions. The platform reaches approximately 4 m/s and reproduces three-dimensional motion without the operational risks of a freely flying drone. Sensors and antennas can be mounted temporarily for controlled measurements. In this study, the platform carries a harmonic radar to evaluate candidate sensor positions for shelf monitoring in the logistics hall.

5 RESULTS AND DISCUSSION

This section presents the results of the scenario-based requirement analysis and the initial system integrations. First, the elicited requirements are consolidated into quantitative profiles and mapped to suitable radar-tag topologies. The section then reports the RoboChief and cable-robot integration results and discusses their industrial implications, current limitations, and remaining validation needs.

Table 1: Target requirements derived for the four logistics reference scenarios.

Scenario	Position accuracy [cm]	Angle accuracy [°]	Update rate [Hz]	Range [m]
Highly dynamic AGV operation	< 5	< 6	50	1–20
Parcel pick-up at metallic station	< 1	< 3	50	0.1–2
SLC shelf monitoring	< 4	< 3	0.1	0.3–5
Production asset tracking	< 10	< 5	1	1–50

Table 2: Mapping of logistics scenarios to suitable radar–tag topologies.

Scenario	Topology	Radar placement	Tag placement	Primary rationale
Highly dynamic AGV operation	Mobile radar	AGVs	Operating environment	Direct, low-latency AGV-relative observations
	Distributed infrastructure radar	Operating environment	AGVs	Reduced AGV-side sensing hardware and computation
Parcel pick-up	Mobile radar	RoboChief	Parcel station	Precise station-relative alignment
SLC shelf monitoring	Infrastructure radar	Cable robot during planning; later fixed	SLCs	Visibility and coverage optimization
Production tracking	Distributed infrastructure	Production area or checkpoints	Assets, working station, tugger train	Wide-area identification and process visibility

5.1 SCENARIO REQUIREMENT PROFILES

Table 1 consolidates the quantitative design targets obtained through the expert process in Section 4. Position and angle accuracy specify the maximum admissible translational and angular errors. The update rate defines how frequently a valid localization or tracking result must be provided. The range denotes the required radar–tag distance coverage. The limits are strict targets, not measurements. Qualitative requirements such as resilience to occlusion, identity association, and scalability remain part of the topology assessment.

Scenario 1 combines a position target below 5 cm and an angular target below 6° with a 50 Hz update rate over 1–20 m range coverage. This profile reflects continuous localization of highly dynamic AGVs across a comparatively large parcel-sorting area. Scenario 2 retains the 50 Hz update rate but tightens the position and angle targets to below 1 cm and 3° . Its short range of 0.1–2 m reflects precise alignment relative to the metallic parcel station rather than area-wide navigation.

Scenario 3 requires position and angle errors below 4 cm and 3° to discriminate neighboring SLCs and shelf positions. Because the inventory state changes slowly, an update rate of 0.1 Hz is sufficient, while the 0.3–5 m range permits observations from candidate infrastructure positions. Scenario 4 relaxes the local targets to below 10 cm and 5° and uses a 1 Hz update rate. Its range extends to 50 m because route and process visibility across a production area take precedence over high-rate motion control. The four profiles therefore expose different priorities and do not support a single topology or sensor placement for all scenarios.

5.2 SCENARIO-TO-TOPOLOGY MAPPING

Figure 3 presents the four logistics scenarios and their candidate radar–tag arrangements. Table 2 converts these

concepts into a traceable topology mapping. The sensing principle is identical in all cases. Radar mobility, tag mobility, placement, and infrastructure density are adapted to each requirement profile. The primary rationale column states the dominant design criterion for each mapping. It is derived from the scenario requirements and the topology characteristics described in Section 3. The column expresses a qualitative design result and does not represent measured performance. The mapping follows the scenario-based requirements and traceability principles used in the methodology [14, 15].

Scenario 1 is illustrated in Figure 3a and supports two topology variants. Setup 1.1 uses a mobile radar on each AGV and stationary tags at known positions. This topology provides direct AGV-relative observations with low sensing latency. An initial mapping step determines the tag coordinates. MoCap supplies reference data during laboratory validation. For the industrial deployment, the tag positions must be measured and calibrated in the operating environment. Setup 1.2 places calibrated radar sensors in the operating environment and one or more tags on each AGV. The infrastructure estimates the AGV pose and communicates the result to the corresponding fleet management system (FMS) or warehouse management system (WMS) platform. This variant reduces onboard sensing hardware and computation. Communication latency and infrastructure availability then affect localization.

Scenario 2 is shown in Figure 3b. It uses a mobile radar on RoboChief and stationary tags at the metallic parcel station. The tags establish a local reference frame during the approach and passage. This arrangement supports the stringent station-relative position and angle requirements in Table 1. Its short operating range limits the required tag infrastructure to the station. MoCap provides laboratory reference data and is excluded from the intended industrial solution. The platform and its initial integration are described in Subsections 4.3.2 and 5.3.1.

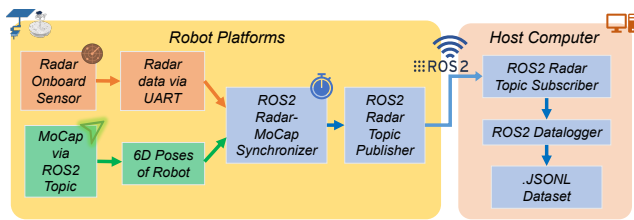


Figure 4: Data acquisition pipeline for recording synchronized harmonic-radar measurements and reference MoCap poses on the robot platforms and host computer.

Figure 3c combines Scenarios 3 and 4. Scenario 3 attaches tags to the SLCs and uses an infrastructure radar for shelf monitoring. During planning, the cable robot moves the radar through repeatable and different positions in front of and above the shelf. The measurements compare tag visibility for different radar positions, shelf occupancies, and tag configurations. Oblique viewing directions are included to address occlusion by shelf beams and adjacent carriers. The resulting coverage assessment identifies positions for a later fixed-radar installation.

Scenario 4 places tags on assets or SLCs, working station, tugger train and distributes radars throughout the production environment. Area-wide installations can provide continuous or zone-level coverage. Sensors at workstations and passages can instead register arrival, departure, and transit events. The selection depends on the required tracking continuity and the acceptable infrastructure density. This mapping supports future multi-sensor and multi-asset experiments in production environments.

5.3 INITIAL ROBOT-PLATFORM INTEGRATION

The initial system integrations realize the radar-tag topologies selected for Scenarios 2 and 3. For Scenario 2, the radar is mounted on RoboChief to support localization relative to the parcel station. For Scenario 3, the cable robot provides a reproducible elevated radar position for assessing shelf-monitoring coverage. Both onboard computing platforms run Robot Operating System 2 (ROS2) Humble, an open-source middleware framework that provides a common communication layer for distributed sensing and robot control [18]. Its communication architecture is based on a graph of modular nodes with standardized interfaces. Publisher nodes send typed messages through named topics, while subscriber nodes receive the corresponding data asynchronously. This publish-subscribe model decouples the radar, MoCap interface, and data logger, allowing each component to operate independently and to be reused on both robot platforms. The resulting node graph and its topic-based data flow are summarized in Figure 4.

The acquisition sequence in Figure 4 comprises five steps. First, the radar transfers its measurement

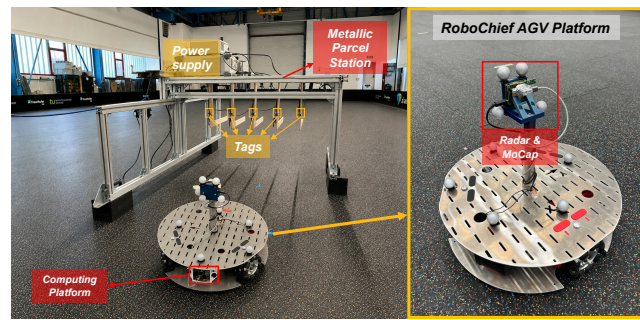


Figure 5: Integration of the harmonic radar on RoboChief for parcel pick-up at the metallic station in Scenario 2.

records through a universal asynchronous receiver-transmitter (UART) connection to the onboard computing platform. Second, the MoCap system provides the time-stamped six-degree-of-freedom pose through the platform-specific ROS2 input topic. RoboChief uses `/robochief01/vicon_pose`, whereas the cable robot uses `/cable_robot/vicon_pose`. Third, the ROS2 Radar-MoCap interface buffers both data streams and assigns the pose with the smallest timestamp difference to each radar record. Fourth, the interface combines the radar data, associated pose, and timestamps in one message. It publishes each synchronized record on `radar/robochief/radar_vicon_raw` for RoboChief or `radar/cable_robot/radar_vicon_raw` for the cable robot. The ROS2 middleware transports these topic messages over the shared Wi-Fi network that connects the robot platforms and host computer. Its Data Distribution Service (DDS) layer handles node discovery and message delivery between the publishers and subscribers [18]. Fifth, the data logger on the host computer subscribes to the corresponding output topic and writes the messages sequentially to a JSON Lines (JSONL) data set in `.jsonl` format. The current effective measurement frequency of the synchronized radar-MoCap records is approximately 9–14 Hz. This frequency depends on the concurrent computational processes and resulting load on the robot's onboard computing platform. MoCap remains a laboratory reference and is not part of the intended industrial solution.

5.3.1 ROBOCHIEF AGV INTEGRATION

Figure 5 presents the harmonic-radar integration on RoboChief within the metallic parcel-station setup of Scenario 2. The harmonic-radar sensor is rigidly mounted on a vertical support at the center of the AGV. A USB cable connects the sensor to the onboard computing platform and transports the serial radar data stream. This platform runs both the RoboChief navigation stack and the Radar-MoCap interface stack in ROS2. The navigation stack executes the AGV motion, while the interface stack acquires the radar messages and associates them with the closest available

MoCap poses according to Figure 4. Five active tags are mounted on the wooden fins of the parcel-loading mechanism and powered individually by an external supply during controlled, tag-wise measurements at every AGV position.

The experiment quantifies station-relative range and angle accuracy and identifies tag positions with low sensitivity to the metallic station structure [19]. RoboChief is aligned with the station center and placed at six defined distances along the approach direction. At each position, the five tags are activated individually, and the radar acquires 100 frequency chirps per tag. Optical markers on RoboChief and the station provide the MoCap reference geometry, while the pipeline in Figure 4 stores the synchronized records for subsequent evaluation. The known tag positions and the measured range and angle provide the observations required to estimate the station-relative pose of RoboChief. The measurement therefore evaluates tag-based harmonic radar as a substitute for the current camera-based localization method at the metallic parcel station.

5.3.2 CABLE ROBOT ASSISTED SHELF MONITORING INTEGRATION

Figure 6 presents the cable-robot integration for shelf monitoring in Scenario 3. The radar sensor and onboard computing platform are rigidly mounted on the cable robot's gimbal platform. Optical markers attached to the radar assembly provide its reference pose through the MoCap system. The overhead power unit of the cable robot supplies both the radar and the computing platform. The industrial shelf measures approximately 2.75 m in width and 2.1 m in height and comprises eight storage levels. Each evaluated SLC carries one active tag on either its front or rear face. An external supply powers the tag through a cable and maintains reproducible operating conditions throughout the measurement sequence.

The evaluation investigates the suitability of an elevated harmonic-radar installation for monitoring tagged SLCs in metallic shelf environments. During each measurement, the cable robot holds the radar approximately 5 m in front of the shelf and at a height of 2.5–3 m. A downward tilt of approximately 10° directs the sensor toward the selected storage bays. This fixed geometry represents a potential ceiling-level installation and enables repeatable comparisons across tag positions, shelf levels, and row depths under consistent observation conditions.

The measurement matrix covers diverse shelf levels and five lateral positions across the shelf width. At each position, the SLC is placed in either the front or rear row, while the tag is attached to its front or rear face. The evaluation considers tag-detection availability, geometric diversity, ambiguity, occlusion sensitivity, and calibration quality. These metrics indicate whether the selected radar po-

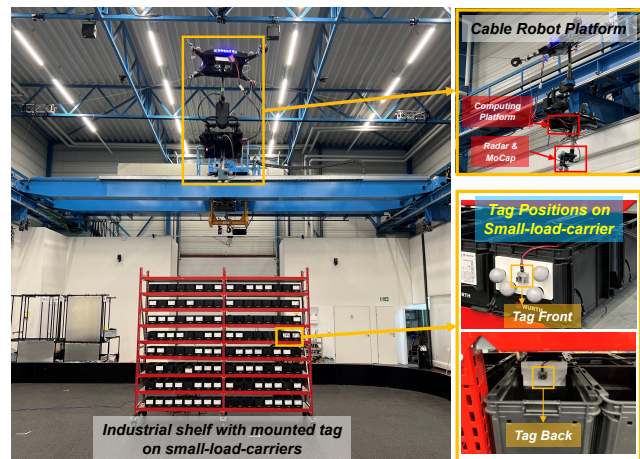


Figure 6: Cable-robot-assisted shelf-monitoring setup for evaluating elevated harmonic-radar sensing in Scenario 3.

sition provides reliable and spatially informative observations within the shelf environment. The common acquisition pipeline records the radar measurements with the corresponding MoCap reference poses and supports subsequent topology validation with fixed infrastructure sensors under representative warehouse conditions.

5.4 INDUSTRIAL APPLICABILITY AND VALIDATION NEEDS

The initial integrations demonstrate complementary deployment modes. On RoboChief, sensing capacity scales with the AGV fleet, while stationary tags provide reusable local references. For shelf monitoring, stationary radar infrastructure reduces onboard hardware for tagged SLCs but requires sufficient coverage and calibrated sensor poses.

The synchronized records in Figure 4 define a common interface between radar acquisition and logistics applications. Standardized factory interfaces can forward observations to fleet, warehouse, inventory, and production-control services. They must preserve timestamps, coordinate frames, tag identity, measurement quality, and configuration metadata. Industrial deployment additionally requires protected tag mounting, reliable power, calibrated radar poses, and maintainable data interfaces at each sensing location during operation and maintenance.

Current evidence is limited to the RoboChief acquisition chain and the cable-robot measurement setup. The requirement profiles are deduced from the experts. Several topology variants in Table 2 remain unimplemented, and the sequential cable-robot procedure excludes concurrent distributed sensing. Fixed multi-sensor trials must therefore assess synchronization, aggregate network load, and mutual radar interference in representative layouts and operating conditions.

6 OUTLOOK

Future work will validate the proposed topology variants across all four logistics scenarios. The Scenario 2 radar–MoCap comparison in the companion European Radar Conference study provides an initial procedure for station-relative AGV localization [19]. Subsequent campaigns will extend this procedure to dynamic trajectories, multiple tags and AGVs, fixed shelf sensors, and production-scale tracking. The experiments will quantify localization accuracy, latency, availability, repeatability, and failure behavior under controlled variations in tag geometry, sensor pose, metallic clutter, occlusion, shelf occupancy, and platform velocity.

Multi-sensor trials will characterize synchronization, mutual interference, data association, and network capacity. Validated observations will be integrated with AGV, warehouse, and production-control systems to assess process safety, throughput, inventory accuracy, and deployment effort. Networked radar observations, tag information, and robot-state data also provide an experimental basis for future 6G-enabled joint communication and sensing. Communication-capable harmonic tags can link 6G cooperative-robot architectures to coordinated mobile and infrastructure sensing [12, 20].

7 CONCLUSION

This paper presented a technical overview and scenario-driven requirement analysis of tag-based harmonic radar for industrial logistics. The four scenarios yield distinct profiles for accuracy, update rate, range, coverage, and identification. The topology mapping demonstrates that no single radar–tag arrangement satisfies all application priorities. Mobile radar with stationary tags supports AGV localization and station-relative alignment, whereas infrastructure radar with mobile tags supports shelf monitoring and asset tracking across production areas.

The initial integrations transfer this mapping to two robot-platform implementations. RoboChief realizes the mobile-radar topology for parcel pick-up at a metallic station. The cable robot provides reproducible sensor positioning for planning a fixed shelf-monitoring installation. Both platforms use a common acquisition pipeline for time-associated radar and MoCap data. Together, the requirement profiles, topology mapping, and platform integrations establish a traceable technical basis for scenario-specific validation and deployment planning under representative industrial conditions and workloads.

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