

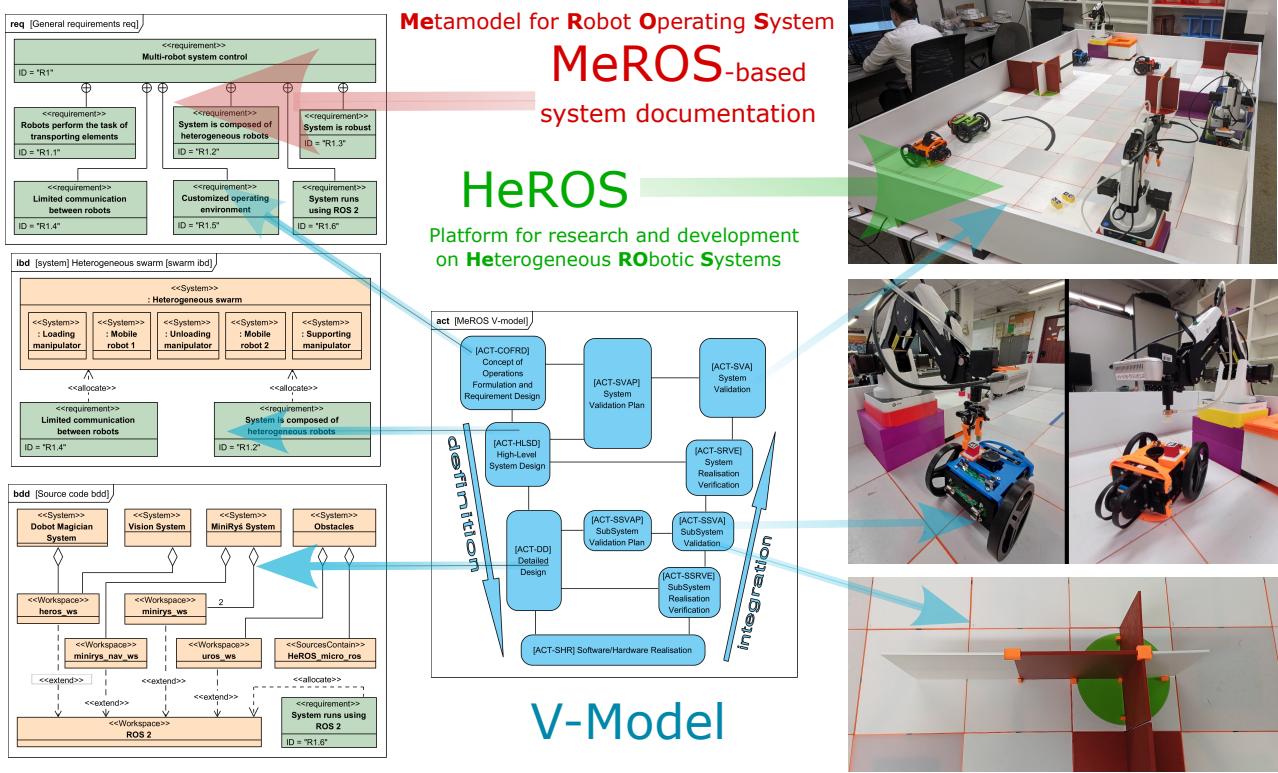
# Graphical Abstract

## ROS-related Robotic Systems Development with V-model-based Application of MeROS Metamodel

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## Highlights

### **ROS-related Robotic Systems Development with V-model-based Application of MeROS Metamodel**

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- Proposal of a System Engineering (SE) V-model adequate for Robot Operating System (ROS) based systems specified according to MeROS metamodel that addresses the most relevant aspects among the variety of V-models developed so far.
- An example of the proposed approach in a complex heterogeneous robot system (HeROS) comprising manipulators, mobile platforms and dynamic, mechanised environment (board).
- Critical discussion of the results in relation to state-of-the-art solutions.

# ROS-related Robotic Systems Development with V-model-based Application of MeROS Metamodel

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## ABSTRACT

As robotic systems grow increasingly complex, heterogeneous, and safety-critical, the need for structured development methodologies becomes paramount. Although frameworks like the Robot Operating System (ROS) and Model-Based Systems Engineering (MBSE) offer foundational tools, they often lack integration when used together. This paper addresses that gap by aligning the widely recognized V-model development paradigm with the MeROS metamodel SysML-based modeling language tailored for ROS-based systems.

We propose a domain-specific methodology that bridges ROS-centric modelling with systems engineering practices. Our approach formalises the structure, behaviour, and validation processes of robotic systems using MeROS, while extending it with a generalized, adaptable V-model compatible with both ROS and ROS 2. Rather than prescribing a fixed procedure, the approach supports project-specific flexibility and reuse, offering guidance across all stages of development.

The approach is validated through a comprehensive case study on HeROS, a heterogeneous multi-robot platform comprising manipulators, mobile units, and dynamic test environments. This example illustrates how the MeROS-compatible V-model enhances traceability and system consistency while remaining accessible and extensible for future adaptation. The work contributes a structured, tool-agnostic foundation for developers and researchers seeking to apply MBSE practices in ROS-based projects.

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## 1. Introduction

The evolution of engineering methods has always aimed not only to improve system performance but also to streamline how systems are designed, verified, and maintained. As robotics matures from early experimental platforms to real-world, often safety-critical deployments, the need for structured engineering practices has become pressing. Modern robotic systems intertwine software, embedded hardware, sensors, and actuators across both simulation and physical domains. While component-level tools in robotics have matured, the methodologies for managing system-level integration and lifecycle traceability remain fragmented [9, 14]. This creates a high entry threshold for developers seeking to apply consistent, traceable, and reusable design patterns across a project.

Systems Engineering (SE), which emerged in large-scale aerospace and defense contexts in the mid-20th century, offers a unifying approach for addressing these challenges [27]. Yet, adapting SE to the realities of robotics – agile workflows, interdisciplinary integration, and hybrid system behaviour – remains methodologically unresolved, lacking widely accepted practices.

In response to growing system complexity, simulation-first design has emerged as a dominant development trend in robotics. It enables early-stage validation and iteration by decoupling software development from hardware availability—supporting rapid prototyping and risk reduction. This shift has been reinforced by the availability of powerful simulators, co-simulation frameworks, and hardware-in-the-loop testing strategies across both academia and industry. However, in many projects, simulation remains disconnected from system-level design, often lacking traceability or lifecycle integration. MeROS was conceived to address this, aiming to reconcile simulation-first pragmatism with structured, model-based engineering discipline.

AI-assisted tooling has recently gained traction in robotics development, particularly in domains such as automatic code generation [45]. While these techniques offer local productivity boosts, they typically operate below the system level—focusing on code rather than model traceability or lifecycle structure.

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Several middleware and software integration frameworks have been developed to manage robotic system complexity [9]. The most widely used among them is the Robot Operating System (ROS), currently in the upgraded and dominant version ROS 2 [32].

ROS exemplifies how modular design, open standards, and collaborative tooling can shape an entire field. Through a loosely coordinated but actively maintained ecosystem – driven by research labs, individual contributors, and major industry stakeholders – it has become the de facto runtime environment in robotics. As Brooks and Kaupp observed, “Standards become powerful when a critical mass of users arise, such that people choose to conform due to the advantages that it brings” [7]. ROS achieved this mass, for integration and reuse – without enforcing formal modeling or lifecycle discipline.

But that very strength also sets its limits. As robotic systems grow in scale, complexity, and criticality, the absence of shared development methods – especially for design traceability, system-level verification, or lifecycle alignment – becomes a structural bottleneck.

Despite advances in simulation tools and runtime environments like ROS, the robotics domain still lacks broadly adopted methodologies for aligning system-level models with executable architectures. This disconnect complicates verification, traceability, and reuse across development cycles.

In this work, we introduce a development method structured around a *MeROS*-tailored V-Model<sup>1</sup>, extending the platform’s existing modeling language [46] with lifecycle guidance that is both rigorous and adaptable. While *MeROS* already delivers a SysML-based language and leverages standard toolchains, it previously lacked a formalized methodology. This contribution addresses that gap – completing the triad described in MBSE literature [17] of an integrated *language, method, and tooling*.

The *V-model* [27, Sec. 1.2.2] is one of the most recognized lifecycle structures in systems engineering. It links system definition steps with matching stages of integration and validation. While it is well known in safety-critical domains, its core principles – refinement, traceability, and structured development – apply more broadly. Many fields, including robotics, use lighter or more iterative forms of the *V-model* to keep development practical while still preserving engineering discipline.

This structural discipline is particularly relevant in safety-aware domains—such as collaborative robotics or healthcare—where compliance with industry safety standards demands traceable and verifiable development workflows. Frameworks like the *V-model* naturally align with these expectations. While *MeROS* does not prescribe a certification process, it offers a structured foundation that supports assurance practices without departing from ROS ecosystem norms.

By defining both a structured development procedure and a standardized system representation, the proposed

framework enables their formal coordination—offering engineers consistent guidance across the entire design flow. Rooted in MBSE principles, this approach builds on prior work in robotics and cyber-physical systems [3], including frameworks like EARL [49] and SPSysML [19]. To our knowledge, it is among the first methodologies that connects a ROS Platform-Specific Metamodel (PSM) to a generalized V-model – establishing a foundation for reusable, traceable, and verifiable system design, while remaining flexible to different workflow contexts.

*Structure of the article:* Section 2 introduces the *MeROS*-tailored V-model and outlines its genesis and structure. Section 3 presents the *HeROS* platform, a heterogeneous multi-robot testbed used for validation. Section 4 illustrates the application of the V-model methodology to a representative robotics scenario using *HeROS* and *MeROS*. Section 5 offers a focused review of related modeling approaches and systems engineering frameworks. Section 6 analyzes *MeROS*’s contributions in context, emphasizing its alignment with emerging trends in simulation, certification, and physical grounding. Finally, Section 6 summarizes our results.

## 2. MeROS-compatible V-model

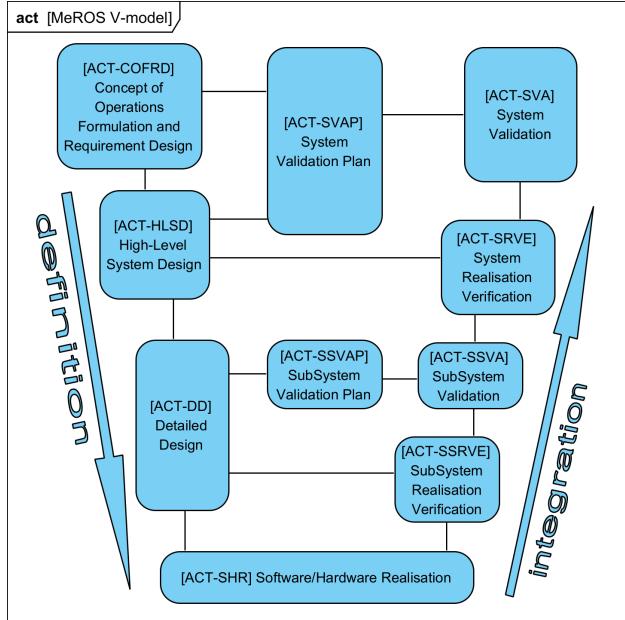
The *MeROS*-compatible V-model formalises a structured development methodology tailored for ROS-based systems, extending the classical V-model principles to address the specific challenges of robotics architectures and SysML-based modeling. By integrating system decomposition, implementation, and verification processes within the *MeROS* ecosystem, it bridges abstract system design and implementation-level details in a traceable and reusable way.

The *MeROS*-compatible V-model (Fig. 1) was designed according to a set of key requirements for usability and methodological coherence. These are denoted as [RV1]–[RV4] below:

- [RV1] – compatibility with diverse interpretations of the V-model, particularly in terms of how Verification & Validation are understood,
- [RV2] – simplicity and generality,
- [RV3] – supports flexible integration into diverse project workflows, without enforcing a specific procedural path,
- [RV4] – possibility of direct application with *MeROS*.

The compatibility requirement [RV1] addresses the broad range of V-model variants found in systems engineering literature. In particular, it reflects differing views on verification – as either a stepwise transition between design stages [41] or a test of conformance between design and implementation [51] – and on validation as the assessment of a realized system against functional and operational expectations [51]. A more detailed discussion of related V-model adaptations appears in Section 5.

<sup>1</sup><https://github.com/twiniars/meros>

**Figure 1:** MeROS-compatible V-model

The order in which the actions from Fig. 1 are invoked crucially depends on the specific project and the assumed design procedure [27]. Hence [RV3], in the description below, we focus on actions rather than sequences of transitions.

## 2.1. System definition with validation plan

This set of actions relates to the definition of the System on the various levels together with the plan of its validation. For this purpose the SysML and UML diagrams are used, in particular created according to the MeROS metamodel.

- **[ACT-COFRD]** – the stage of Concept of Operations (ConOps) formulation and Requirement Design is the level at which, in principle, elements defined directly in MeROS are not used. The specification primarily employs: (i) requirements diagrams, and behavioural diagrams – (ii) use case diagrams, (iii) activity diagrams and (iv) sequence diagrams (see [38] for SysML diagrams taxonomy details). These are the basis for both the formulation of the validation plan [ACT-SVAP] and the overall design of the System [ACT-HLSD] and its individual parts [ACT-DD]

It should be noted that requirements formulated in this stage should be allocated in the subsequent phases of system definition.

- **[ACT-HLSD]** – In this stage the general view of the System specification is presented consistent with concept and requirements formulated in [ACT-COFRD]. Here, the MeROS-related elements are introduced. The main System is defined in general way, i.e., especially its internal Systems and Communication Channels are introduced. For that purpose all of the SysML

diagrams are helpful, with emphasis on block definition diagram, internal block diagrams, activity diagrams, sequence diagrams and use-case diagrams.

- **[ACT-SVAP]** – The plan of the whole System validation. Its specification can be supported by behavioural diagrams, especially sequence diagrams. The plan can be specified in terms of the System Concept [ACT-COFRD], or High-level System Design [ACT-HLSD].
- **[ACT-DD]** – Here, the general view of the System formulated in [ACT-HLSD] is decomposed and specified with more detailed elements. For example, the structure of hight-level SubSystems and generic Communication Channels are modeled using specific ROS communication interfaces: Topics, Services, and Actions. Similarly, the internal system behavior can be described at the level of ROS Nodes and their interactions.
- **[ACT-SSVAP]** – The validation plan for the particular SubSystems and its parts validation, created in the way analogous to [ACT-SVAP] according to [ACT-DD].

## 2.2. System realisation with verification and validation

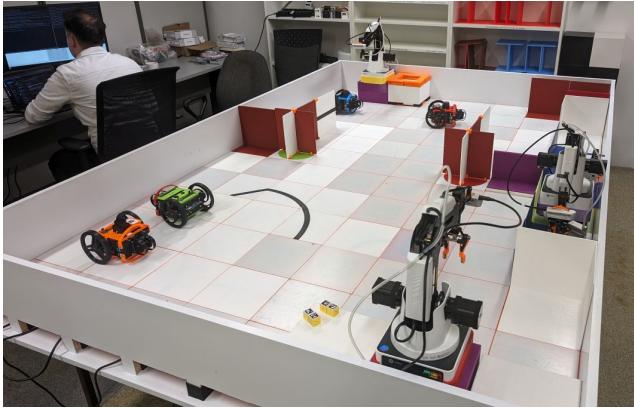
The actions below relate to System Realisation. It should be noted that this encompasses not only physical implementations but also simulation-based models (often referred to as digital twins when integrated with real-time data).

- **[ACT-SHR]** – Realisation (implementation) of the System design both of the software and hardware.
- **[ACT-SSRVE]** – Verification of the architecture (structure and behaviour) of particular Systems and its parts.
- **[ACT-SSVA]** – Validation of the particular Systems and its parts functionalities according to the plan specified in tagref [ACT-SSVAP].
- **[ACT-SRVE]** – Verification of the architecture (structure and behaviour) of the whole System.
- **[ACT-SVA]** – Validation of the whole System functionality according to the plan specified in [ACT-SVAP].

## 3. HeROS platform

*HeROS* – The miniaturised, low-cost physical test platform for heterogeneous robotic systems [48] (Fig. 2) was created as the application of small-scale robotic testbed [50] with the specific features:

- modular, tile-based board that facilitates the easy reproduction of experiments in various environmental configurations,
- tiles small enough to construct complex test environments within standard building spaces,



**Figure 2:** HeROS board and robots in the form used in the experiments presented in this article

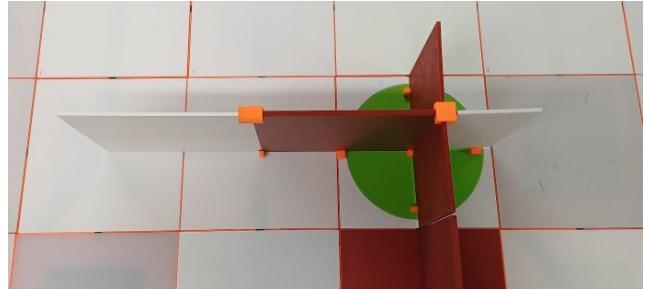
- easy access to the interior of the board from all sides,
- moderate board price with small-scale manufacturing,
- simple to produce and modify,
- the possibility to route cables underneath the tiles,
- mobile robots that match the dimensions of the board tiles,
- manipulation robots that are compatible with the dimensions of the board tiles,
- unified software framework for all of the hardware.

### 3.1. Board with tiles

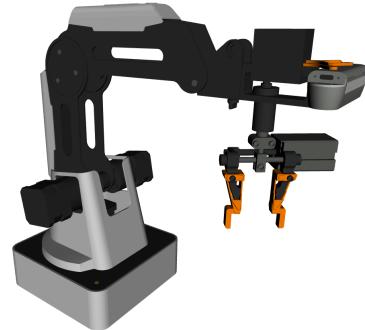
The board is constructed using 3D printed legs, bases, and tiles. The environment is surrounded by wooden walls. In its current form, the board's legs are 10 cm high. Thanks to this, it is possible to place any vulnerable components required to power the robots and utilise the environment in a secure and isolated space. Each base is held up by 4 legs and fits one square-shaped, 20 cm wide tile. Currently possessed tiles include flat floor tiles (with different markings for purposes of various robotic applications and tiles with 20 cm high walls, turns or bends. This allows for building complex testing environments in finite space. Furthermore, the mechanical sliding rail, utilises together with the Dobot robot (Subsection 3.3), was also integrated into the board. In its current state, the board can be used for designing test environments of up to 160 by 240 cm in size.

### 3.2. Mechanised obstacles

Moving obstacles can be placed on the board to dynamically reconfigure the operating environment. Components in the form of 3D printed walls and a rotating platter were used to construct the moving obstacles. An example of the designed moving obstacle in the shape of the letter “T”, positioned horizontally on the plate shown in Fig. 3. It is actuated by a DC motor with a gear, mounted in a dedicated socket beneath the plate. In the experiments considered in this article, there are two such obstacles on the board, together forming a double-leaf gate in the middle of the board. Obstacle control is realised using the *ESP-32* microcontroller and the micro-ROS [4] framework.



**Figure 3:** Rotating obstacle (top view)



**Figure 4:** Customised Dobot Magician robot - visualisation

### 3.3. Customised Dobot Magician robot

The *Dobot Magician* is a 4-DOF serial educational manipulator developed by Dobot (Fig. 4). It supports various end-effectors, including a two-finger gripper, a pneumatic suction cup, and a soft gripper. Our manipulators were enhanced with custom 3D-printed accessories – such as gripper extenders, a mount for the Intel RealSense D435i depth camera, and fixtures for signal cables and compressor tubing – all integrated into the ROS 2-based control system and movement planner. Furthermore, a ROS 2-based control system with a graphical user interface was implemented<sup>2</sup> to expand the robot's functionality [31]. The kinematic configuration of the Dobot Magician makes it particularly well-suited for standard *Pick&Place* operations, i.e., straightforward point-to-point object manipulation tasks.

### 3.4. MiniLynx mobile robot

The *MiniLynx*<sup>3</sup> (*MiniRyś*) is a small differential-driven mobile robot (Fig. 5) designed for research and development of multi-robot systems. It has the ability to drive in two modes of locomotion: a vertical mode, where the robot balances on two wheels, and a horizontal mode, where the third point of support is one of the bumpers. The robot is characterised by its ability to detect obstacles, map its surroundings using the SLAM algorithm, navigate autonomously and collaborate with other units to perform swarm navigation tasks. It also includes a variety of sensors such as LiDAR, an RGB camera and an IMU, and its computing unit is a

<sup>2</sup><https://vimeo.com/793400746>

<sup>3</sup><https://vimeo.com/1052300450>



Figure 5: MiniLynx (MiniRyś) robot

Raspberry Pi 4B single board computer. The robot's software architecture is built upon the ROS 2 components: down from locomotion control and sensors processing up to with navigation functionalities managed by the Nav2 system, which is an integral component of ROS 2's navigation stack.

## 4. Application

The concept of the V-model makes it possible to systematically organise the development process of a multi-robot system, and facilitates the connection between the system definition stage and the integration and testing stage. In the following the development process of multi-robot heterogeneous system was chosen as a representative example.

The purpose of the following description is to highlight representative actions from the proposed V-model, rather than covering the full project in detail.

### 4.1. Concept of operations formulation and requirements design [ACT-COFRD]

This case study was developed as a demonstrator for the proposed methodology and as a validation scenario for the *HeROS* research platform. While synthetic in setup, the scenario emulates real-world multi-agent logistics tasks in constrained and dynamic environments – providing a representative testbed for structured modeling and validation using MeROS and the V-model.

The mission involved coordinated cooperation between heterogeneous robots: two mobile *MiniLynx* robots and three *Dobot Magician* manipulators. Robots shall cooperatively accomplish the task of transporting cubes from one end of a board to the other. The system should continue to operate despite a failure of one mobile robot and adapt to changes in the operational environment. The operational board layout is shown in Fig. 6.

Fig. 7 presents the general requirements for the designed system. The primary requirement is the use of heterogeneous robots [R1.2], which have limited ability to communicate with each other [R1.4]. In addition, the created system should be robust [R1.3] and should have the capability to

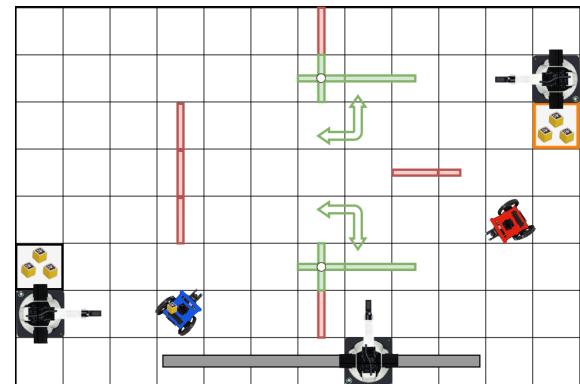


Figure 6: Operating environment layout (top view)

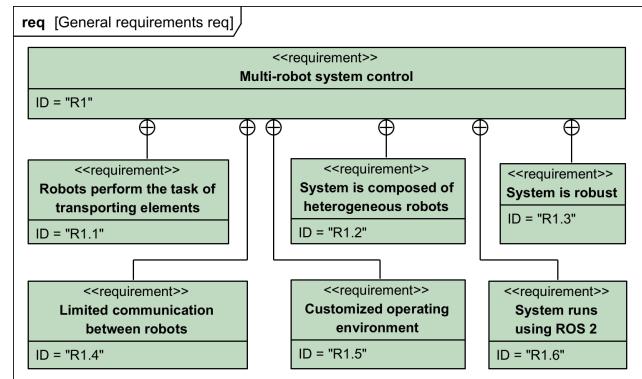


Figure 7: General requirements for the designed system

adapt to the changing environment in which it operates. Regarding the software side, system should be based on ROS 2 [R1.6].

It is also worth to clarify the requirements [R1.1] and [R1.5]. The first one specifies the class of the task performed by the robots - it will be the transportation of items. This task will be executed in custom operating environment [R1.5].

### 4.2. High level system design [ACT-HLSD]

Having formulated the requirements, it is time to describe the system's operation at the highest possible level – at this point, we do not want to go into details. The operation of the system can be shown on behavioural diagrams – in this case, activity diagrams. Describing individual behaviours should be preceded by identifying the actors/components that will perform these behaviours and interact with each other. Fig. 8 distinguishes a system in the form of a multi-robot research platform, which consists of two systems: a *Heterogeneous swarm* system and a *Modular environment* system. The *Heterogeneous swarm* system consists of three *Manipulator* systems and two *Mobile robot* systems. One system (*Obstacles*) is specified as part of the *Modular board environment* system.

There is no explicit peer-to-peer communication in the system; therefore, no communication channels are depicted in Fig. 9. Instead, coordination emerges implicitly: there is

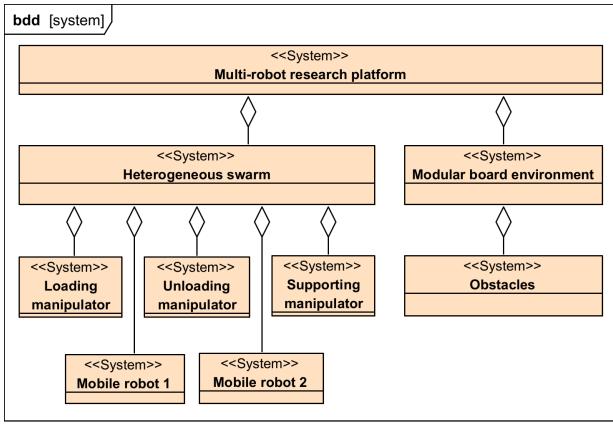


Figure 8: Hardware-oriented systems composition

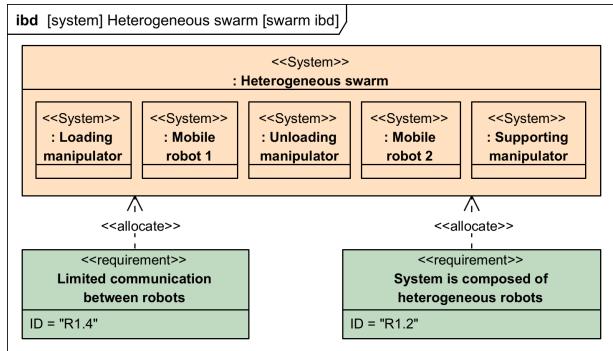


Figure 9: Internal block diagram for a heterogeneous swarm system

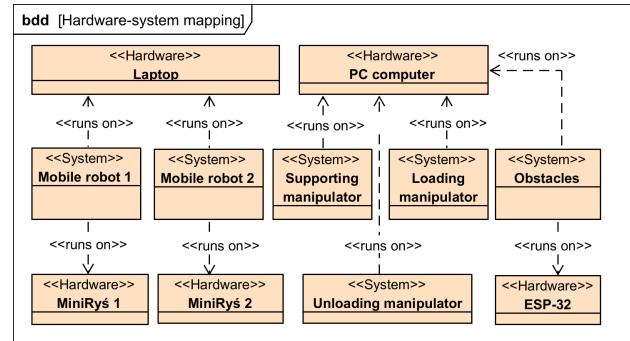


Figure 11: System-hardware mapping

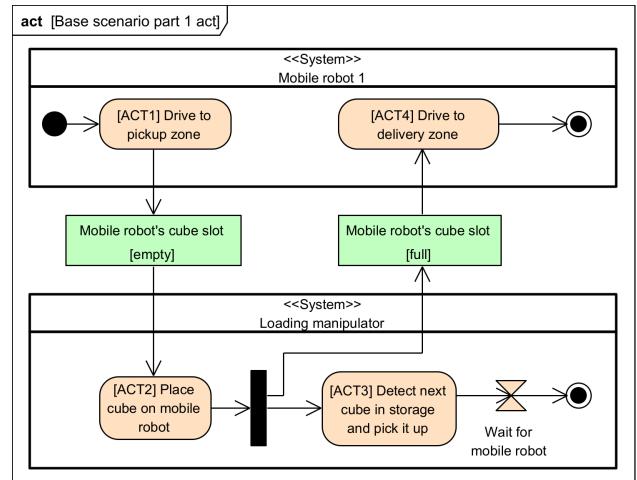


Figure 12: General operation of the system (part 1)

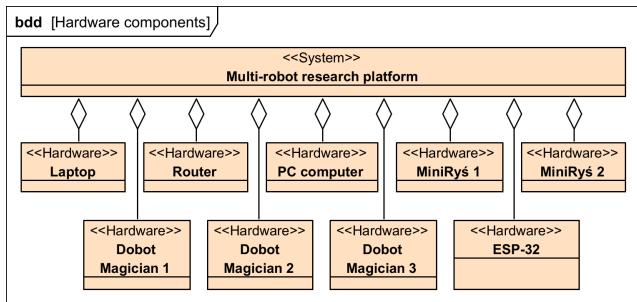


Figure 10: System hardware components

no centralized controller, and the shared medium of communication is a physical cube, whose presence can be detected by both mobile robots and manipulators.

Before discussing the behavioural aspects of the system, it is still necessary to look at its hardware part. Fig. 10 presents at a general level the hardware-network configuration of the realised system. Fig. 11 shows which parts of the System are running on which hardware components.

As the basic behaviour of the *swarm*, *mobile robots* were chosen to perform the task of transporting cubes between *manipulators* units. The flow of this behaviour was divided into two activity diagrams shown in Fig. 12 and Fig. 13.

In its initial state, the *Loading manipulator* holds a cube in its gripper. It is positioned so that the manipulator's camera can observe the environment i.e. a section of the board. In this way it waits until the *mobile robot*, which is driving towards it [ACT1], comes within its operational range of movement. The robot does not explicitly notify readiness to load – the *Loading manipulator* infers based on analysis of the data from its own camera. When the mobile robot is within the manipulator's range, the manipulator places a cube onto it [ACT2], and subsequently retrieves another cube from warehouse [ACT3]. The mobile robot, based on the readings from the LiDAR, realises that a cube is on it and moves in the direction of the *Unloading manipulator* [ACT4].

At the same time, on the opposite side of the board is an *Unloading manipulator* and a *second mobile robot* that transports a cube on itself. This robot navigates autonomously to the manipulator [ACT4], which observes the board with a camera. When the mobile robot is in range of the manipulator, the *Unloading manipulator* will remove the cube [ACT5] from it and drop it into the container [ACT6]. The *mobile robot* will realise on its own that it no longer carrying the cube on it and will move in direction of the *Loading manipulator* [ACT1].

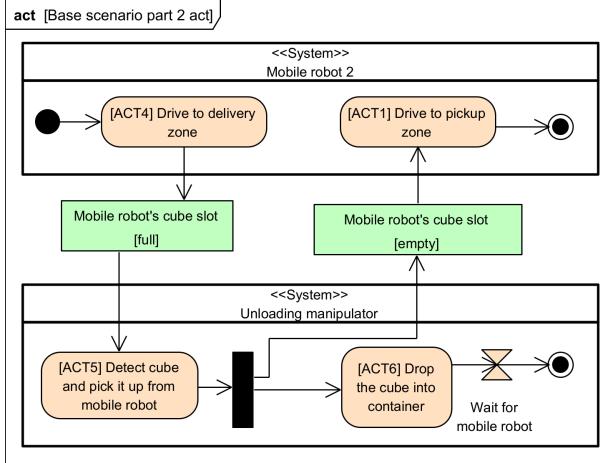


Figure 13: General operation of the system (part 2)

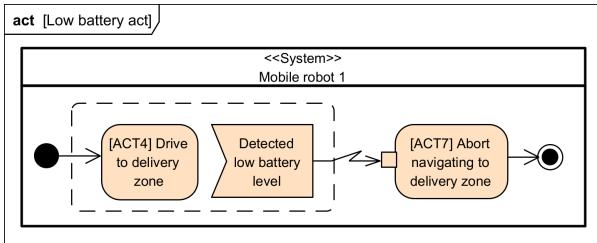


Figure 14: Mobile robot failure case. Example for Mobile robot 1

The behaviour depicted in Fig. 14 describes an emergency situation in which a *mobile robot* may find itself while performing a task, i.e., *battery discharge*. Mobile robots continuously monitor the voltage level on their batteries. While driving to one of the manipulators (in this case, the *Unloading manipulator* [ACT4]), it may happen that the level is too low to continue driving. In such a situation, the robot should *abort the movement action* to the target point.

The most extensive set of behaviours is shown in Fig. 15. It describes a scenario in which the operational environment changes dynamically during the scenario execution. In such a case, a *third Dobot Magician manipulator*, mounted on the sliding rail, is used to support the other robots in performing their task. The set of behaviours depicted in the diagram begins identically to the general operation of the system. At some point, the system tester deliberately modifies the environment [ACT8]. Using remote-controlled *moving obstacles*, he sets them up in a way that *divides the test environment* into two parts. The two *mobile robots* are *not able to reach* their target in this situation. When the navigation systems' global planners' attempt to generate a new trajectory fails, they *go to their recovery points*.

Each *MiniLynx* robot has a predefined *recovery point* stored in memory – an emergency location to move to if a task cannot be completed [ACT9]. These points lie within the operational range of the *Supporting manipulator*, which moves along a sliding rail and continuously observes its surroundings via a camera. When the first *MiniLynx* robot

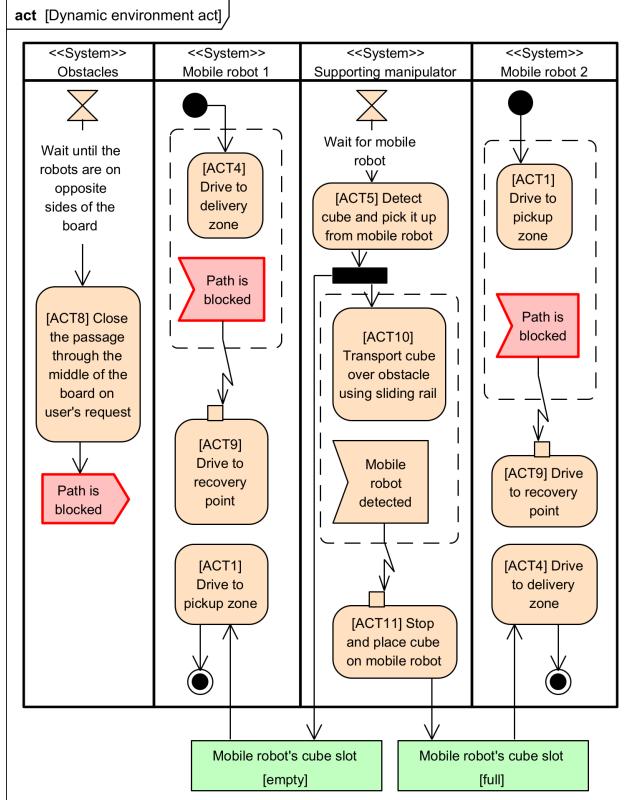


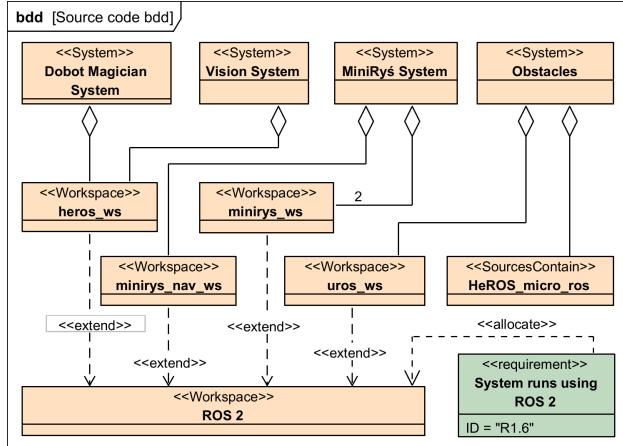
Figure 15: Occurrence of changes in the operational environment

encounters an obstacle and cannot proceed to the delivery zone, it drives to its recovery point. Once there, the *Supporting manipulator* detects the robot and *removes the cube* from it [ACT5]. It then lifts the cube high as possible and begins movement along the sliding rail to *transport the cube over the obstacle* [ACT10].

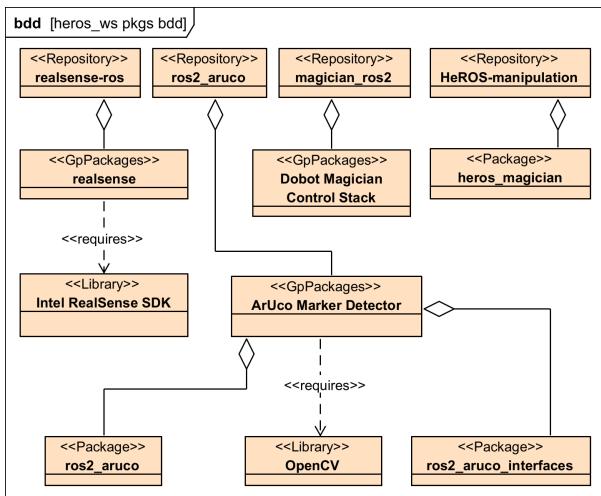
At the same time, the *MiniLynx*, from which the cube has been removed, moves to the *Loading manipulator* for another cube to be transported [ACT1]. Meanwhile, the *Supporting manipulator* waits until the *second MiniLynx* robot reaches its own recovery point. If the second robot has not yet arrived, the manipulator will *pause at the end of the rail*. It will wait there for the *MiniLynx*, and when it appears within the manipulator's range, it will put the cube down on it [ACT11]. After getting the cube *MiniLynx* will drive with it directly to the *Unloading Manipulator* [ACT4], and the *Supporting manipulator* on the sliding rail will return to its initial position.

#### 4.3. Detailed design [ACT-DD]

The Detailed design [ACT-DD] stage focuses on structurally specifying the system architecture, elaborating on diagrams developed during the High level system design [ACT-HLSD] stage. This includes planning the division of source code into packages, repositories, and workspaces, identifying *subsystems* within each *system*, and defining



**Figure 16:** Source code divided into workspaces and repositories



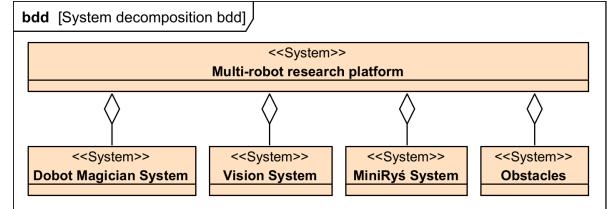
**Figure 17:** ROS 2 packages located inside heros\_ws workspace

communication interfaces between them – preferably illustrated using internal block diagrams. The MeROS metamodel facilitates this structural specification by providing a dedicated modelling layer for architectural elements, as demonstrated in Fig. 16 and Fig. 17. As part of this stage, verification is performed progressively across description layers, including the allocation of requirements.

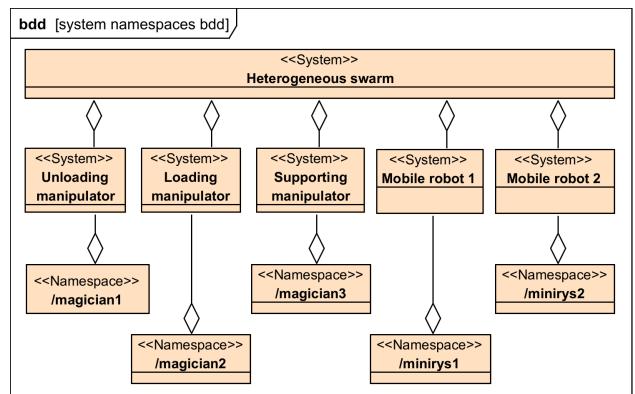
Fig. 18 presents the *component systems* of a *multi-robot system*. The division line adopted is strictly *software-related*, unlike the division in the Fig. 8, which separates systems by the *function* they perform. *Dobot Magician System* and *Vision System* are systems associated with Dobot Magician manipulators. The *MiniRys System* refers to mobile robots, and the *Obstacles* System refers to moving obstacles that are part of the test environment.

The individual mobile and manipulator robot systems are deployed in namespaces as shown in the Fig. 19.

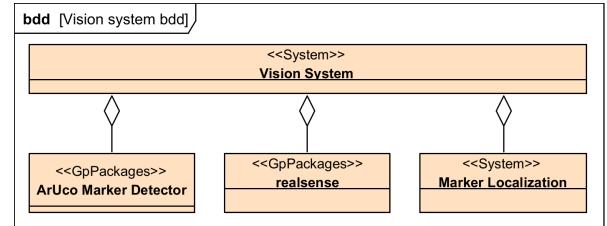
The *Vision System* represented in Fig. 20 by the *Vision System* block consists of source code divided into ArUco



**Figure 18:** Systems composition oriented towards major software components



**Figure 19:** Systems with assigned namespaces



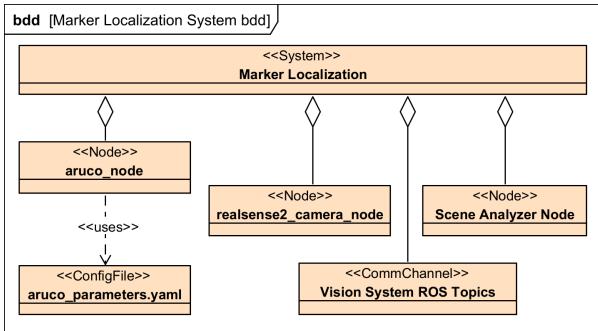
**Figure 20:** Vision system composition

Marker Detector and Intel RealSense Groups of Packages and the *Marker Localisation* system.

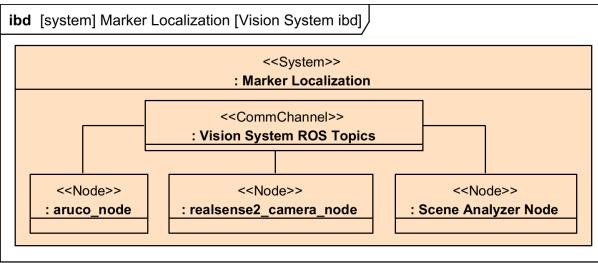
The *Marker Localisation* system, whose components are presented in the Fig. 21, consists of three ROS 2 nodes that exchange data using a topics mechanism. The aruco\_node is responsible for AR-marker detection. It requires parameters contained in a *YAML file* to be passed to it. The realsense2\_camera\_node communicates with the camera and publishes the image stream acquired from it. The *Marker Localisation* system also includes a dedicated Scene Analyzer Node, which is responsible for *analyzing the observed environment*. Based on the camera image, it determines whether the mobile robot is ready to receive or return the cube.

The internal block diagram in Fig. 22 specifies how the ROS 2 nodes that are components of the *AR-Marker Localisation* system communicate with each other.

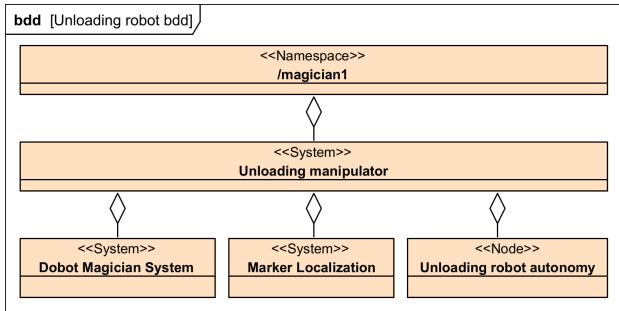
The first robotic system described will be the *Unloading manipulator* system responsible for picking up cubes from mobile robot. The system structure of this manipulator is



**Figure 21:** Structure of the AR-marker localisation system



**Figure 22:** Internal blocks diagram of AR-marker localisation system



**Figure 23:** Composition of systems in /magician1 namespace

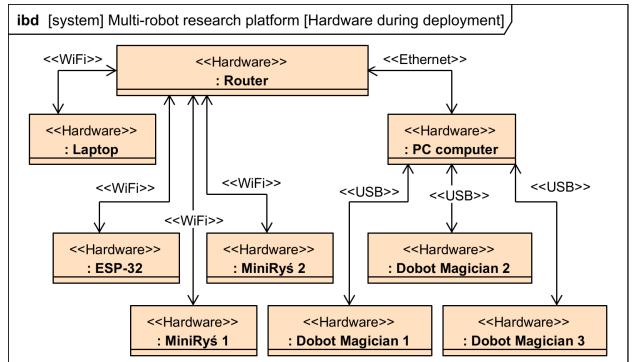
depicted in the Fig. 23. It is launched in the namespace of the `/magician1` which ensures the uniqueness of the names of, among others, the topics and nodes of this system. The system consists of the *Dobot Magician* manipulator controller, the *Marker Localisation* system, and the custom Unloading robot autonomy node, which is responsible for *selecting the robot's behaviour* in response to external stimuli.

As part of [ACT-DD] stage, it is also important to plan how the *hardware-network* architecture of the designed system will look like (Fig. 24).

#### 4.4. Software/Hardware realisation [ACT-SHR]

The realisation of the system can be divided into *software* and *hardware* parts. As for the software, it was based on ROS 2 (Humble Hawksbill distribution [39]). The high-level part of the software was written in Python. C language was used to program the microcontroller.

In this work, we followed ROS Enhancement Proposals (REPs)[16], primarily REP 144 and REP 135, to ensure



**Figure 24:** Hardware-network architecture of multi-robot system

compliance with established standards in ROS 2 development. REP 144 was followed to ensure a standardises package structure and consistent naming practices. Additionally, REP 135 was applied to standardise the use of namespaces and naming patterns, ensuring organises and unambiguous identification of nodes and topics in the ROS 2 ecosystem.

The *hardware* part required designing and printing 3D components (accessories for the manipulator and mobile robots, moving obstacles and parts of the environment). *Cameras* had to be mounted on the *manipulators*, as well as extenders for *two-finger grippers* that made it easier to grasp the cube. Two *DC motors*, a two-channel *motor controller* and an *ESP-32* microcontroller were used to *control the moving obstacles*.

#### 4.5. Subsystem realisation verification [ACT-SSRVE]

The *Subsystem* realisation verification [ACT-SSRVE] stage involves the comparison of the compatibility of the realised architecture with its design. In the case of ROS-based systems, this is a check of the compatibility of names for topic, nodes, namespaces etc. Since this is the stage of *subsystems* verification, it should be limited to checking that the individual nodes are properly connected to each other, not individual systems.

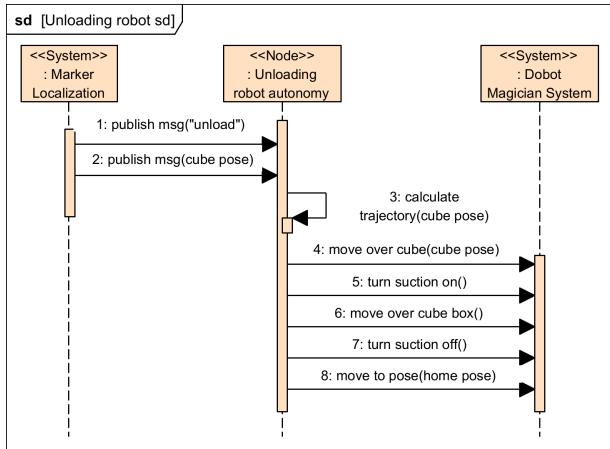
ROS 2 provides a wide range of tools – both graphical user interface (GUI) and command-line interface (CLI) – enabling introspection of the running system. From GUI tools, it is worth using `rqt_graph` to visualise nodes and topics. From the CLI tools, it is best to choose '`ros2 node info <node_name>`' and '`ros2 topic info <topic_name>`' and confront it with the system design.

At this stage, you should also verify the correctness of package names and compliance with the planned division of code into repositories, packages and workspaces.

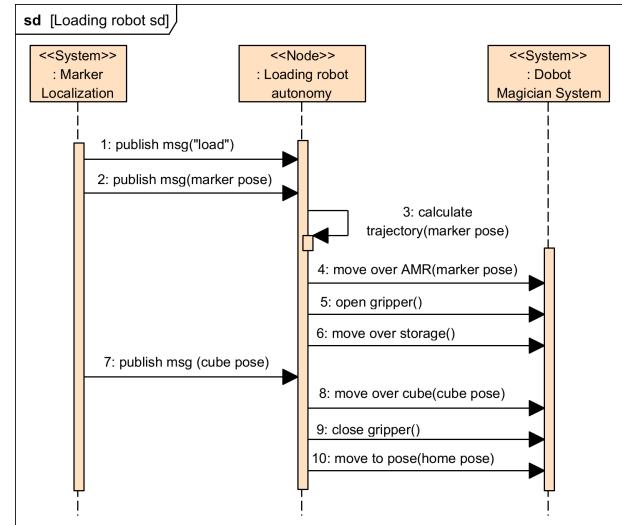
In the system described in this article, the above-mentioned tools were used, which made it possible to successfully carry out the [ACT-SSRVE] stage.

#### 4.6. SubSystem Validation Plan [ACT-SSVAP]

This stage involves planning various test scenarios to validate the system's operation. The result of this work should



**Figure 25:** Sequence diagram for unloading a cube from a mobile robot (video at 0:35): [vimeo.com/977486838](https://vimeo.com/977486838)



**Figure 26:** Sequence diagram for placing a cube on a mobile robot (video at 0:29): [vimeo.com/977486838](https://vimeo.com/977486838)

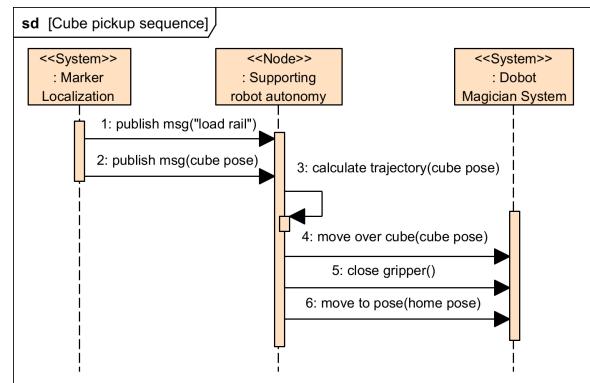
be a set of behavioural diagrams, which will be used in the next stage of the proposed procedure. The test scenarios were derived from the system requirements (Fig. 7).

Fig. 25 shows the sequence of operations performed when picking up the cube from the robot. The *Unloading robot autonomy* node will only *initiate picking* of the cube when the *mobile robot stops moving*. The picked cube is dropped into a box standing on the left side of the robot. Finally, the *Unloading robot* returns to the base (home) position, in which the camera covers a fragment of the board in front of the robot.

The sequence of operations for placing a cube on a mobile robot is depicted in Fig. 26. The process follows these stages: (1) the *Marker Localisation* system sends a load message to initiate the sequence; (2) the *Loading robot autonomy* node retrieves the AR-marker position attached to the mobile robot; (3) it calculates an approach trajectory; (4) the manipulator moves above the mobile robot; (5) a signal is sent to open the gripper; (6) the arm moves above the cube storage area; (7) the *AR-marker detection* system provides the position of the target cube; (8) the manipulator moves above the cube and picks it up; (9) the gripper closes; (10) finally, the arm returns to a base observation pose, from which it monitors the board for the next incoming mobile robot.

The sequence diagrams shown in Fig. 27 and Fig. 28 depict the sequence of operations performed by the Supporting manipulator. The role of the *Supporting manipulator* is to *transfer a cube* from one mobile robot to another in situation when the environment is impassable. When the Supporting robot autonomy node receives a message from the *AR-marker localisation* system, the robot will *pick up the cube* from the *first mobile robot*. It will then start *moving along the rail* until it encounters a *second robot* on which it can *put the cube down*.

The sequence of operations performed by the *ESP-32* microcontroller while moving the obstacle is shown in diagram Fig. 29.



**Figure 27:** Sequence diagram for the supporting manipulator picking up a cube (video at 2:08): [vimeo.com/977486838](https://vimeo.com/977486838)

#### 4.7. Subsystem realisation validation [ACT-SSVA]

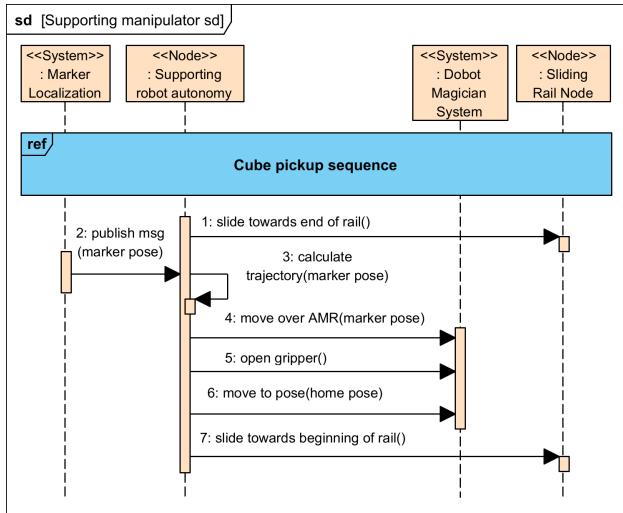
Validation takes place at various levels of the V model and confirms the functionality of individual components and the system as a whole. As part of Subsystem realisation validation [ACT-SSVA], the subsystems' functionality was tested based on the test scenarios specified during [ACT-SSVAP] stage.

Validation was successful for all test scenarios. The most relevant fragments from the execution of the test scenarios are presented below in the form of the following snapshots:

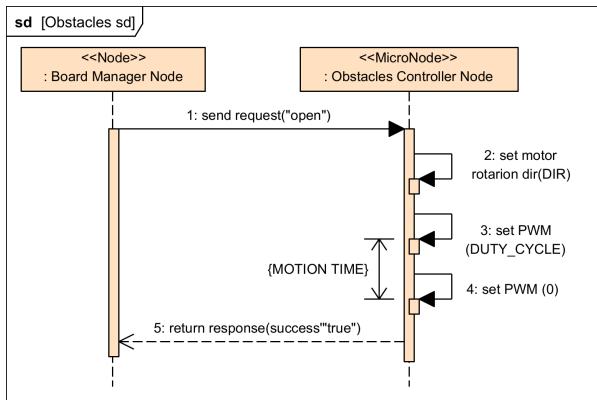
- manipulators picking and placing the cube (Fig. 30)
- manipulator mounted on sliding rail supports mobile robots (Fig. 31)
- mobile robots unable to continue the task (Fig. 32)

#### 4.8. System verification [ACT-SRVE]

At this stage, we verify integration between subsystems, focusing on the compatibility of topics and interfaces that



**Figure 28:** Sequence diagram for transporting a cube over an obstacle (video at 2:08): [vimeo.com/977486838](https://vimeo.com/977486838)



**Figure 29:** Sequence diagram of operations performed when moving an obstacle (video at 1:24): [vimeo.com/977486838](https://vimeo.com/977486838)

connect them. Tools used are the same as in [ACT-SSRVE], now applied at the system level.

#### 4.9. System Validation Plan [ACT-SVAP]

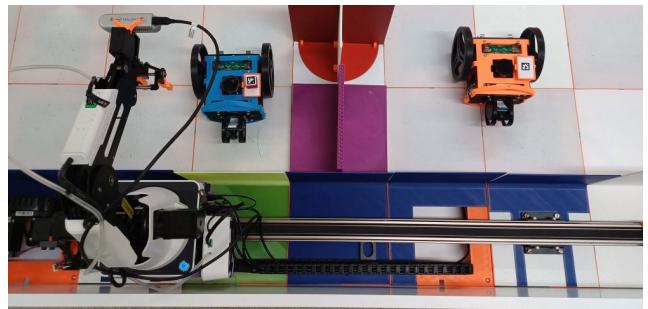
A validation scenario to test the system's performance is shown in Fig. 33. It consists of five parts; we will focus on the fourth part (the penultimate one) because it is the most elaborate and therefore the most representative.

The scenario describing the operation of the system in a changing environment consists of two sub-scenarios (Fig. 34). The first describes the robots' reaction to the reconfiguration of the environment, and the second describes the role of the supporting manipulator.

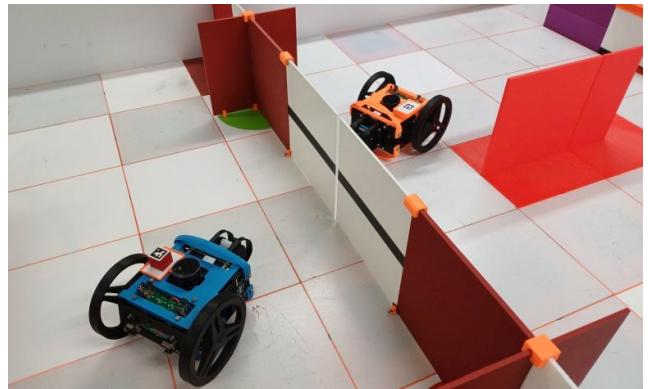
Sequence diagrams describing the aforementioned sub-scenarios are shown in Fig. 35 and Fig. 36. An element of validation was to annotate in the following diagrams the activities that were specified at the stage of conceptualizing the system operation.



**Figure 30:** Cooperation of mobile robots and manipulators



**Figure 31:** Mobile robots waiting for support from manipulator mounted on sliding rail



**Figure 32:** Closed gate preventing mobile robots from driving to the other side of the board

#### 4.10. System validation [ACT-SVA]

System validation [ACT-SVA] is the final step of our proposed V procedure. It involves checking the functionality of the system as a whole. Validation tests were carried out according to the test scenarios specified during [ACT-SVAP] stage, which were created based on the requirements described within [ACT-COFRD] stage.

The video recorded during execution of the validation scenario is available at the link <https://vimeo.com/977486838>.

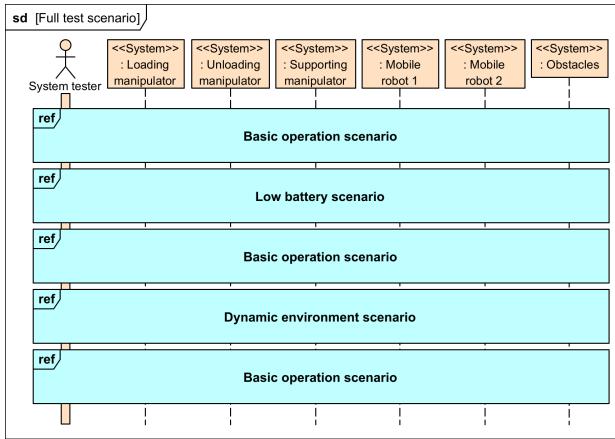


Figure 33: Full test scenario

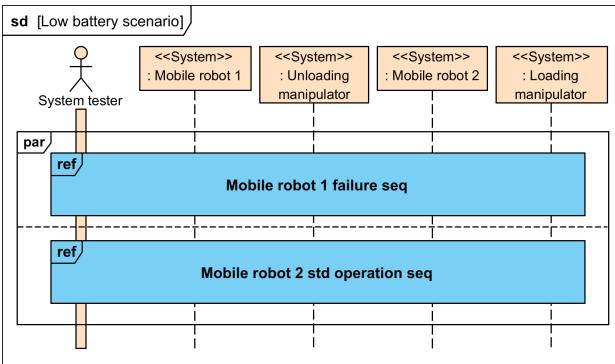


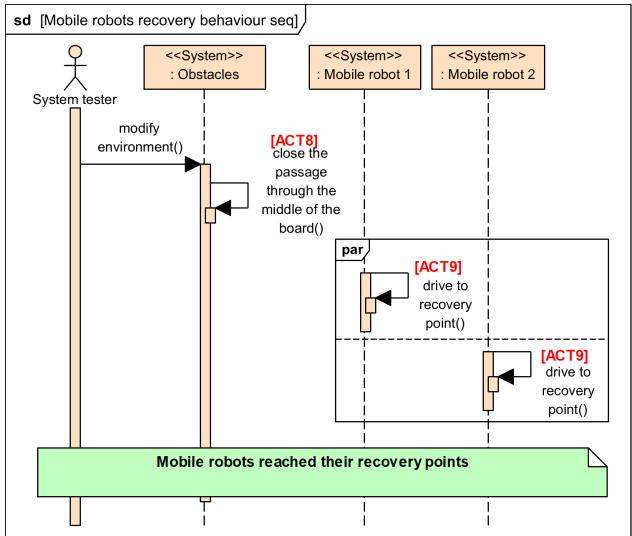
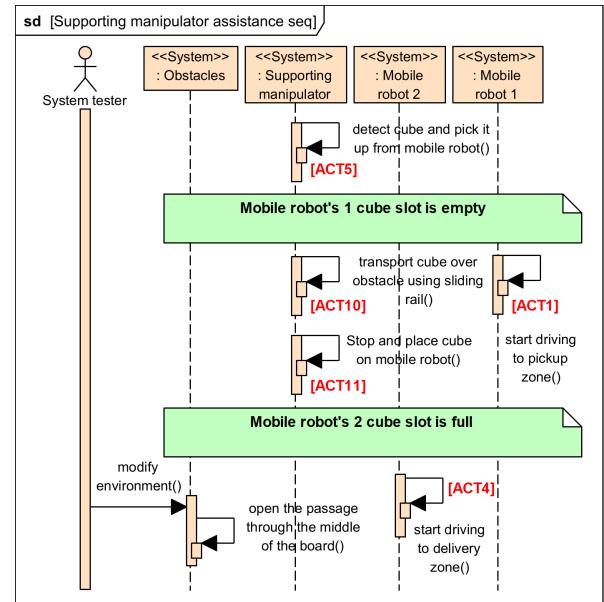
Figure 34: Sequence diagram considering the occurrence of changes in the environment

## 5. Related Works

Robotics software development has followed distinct lineages, shaped by shifting priorities – such as standardization, real-time execution, and lifecycle modeling. Many platforms have emerged in the past two decades [35, 3], but most emphasize runtime integration over system-level traceability or verification – especially in open-source projects.

Despite fragmentation, many frameworks rely on a shared runtime foundation: the *Robot Operating System (ROS)*. ROS standardizes component execution and communication but does not support modeling, verification, or traceability. It acts as an infrastructure layer, not a systems methodology. This has enabled remarkable scaling and reuse, yet also left room for complementary frameworks that address lifecycle-level engineering. Approaches such as *MeROS*, *MROS*, and *ISE&PPOA* reflect this next phase in model-driven robotics.

Many of these efforts emerged from technical needs — such as distributed control, modularity, or real-time guarantees — rather than from certification pressures. However, as robotics systems enter regulated domains, their development increasingly intersects with safety and assurance standards (e.g., ISO 13482, IEC 61508, UL 3300 [28, 26, 43]), which

Figure 35: Sequence diagram describing the reaction of mobile robots to changes in the environment (video at 1:24): [vimeo.com/977486838](https://vimeo.com/977486838)Figure 36: Sequence diagram representing the role of the supporting manipulator in the cube transport task (video at 2:09): [vimeo.com/977486838](https://vimeo.com/977486838)

require documented lifecycle traceability, structured verification pathways, and architectural accountability. These demands are naturally aligned with the V-model philosophy. Yet, few community-maintained frameworks address such requirements directly. This gap has motivated research into methods and tooling that blend ROS-native practices with lifecycle modeling — a niche into which *MeROS* has been specifically developed, aiming to provide structured modeling without departing from ROS ecosystem norms.

To trace how these frameworks evolved, we group them into three problem-focused lineages:

- **Middleware/Standardization:** CORBA-based ecosystems emphasizing distributed execution and interface standardization (e.g., *OpenRTM*, *OPRoS*).
- **Runtime Execution:** Frameworks prioritizing real-time operation, code modularity, and safety – without formal modeling (e.g., *Orocос*, *GenoM*, *BCM*).
- **Model-Driven Lifecycle:** SysML/UML-based modeling environments supporting early-stage design, traceability, and validation (e.g., *ISE&PPOA*, *MROS*, *PDD*, *MeROS*).

These frameworks differ in scope – from full middleware stacks to abstract modeling tools – but share common challenges: ensuring modularity, reuse, and verifiable system integration. As Table 1 illustrates, no single lineage fully reconciles lifecycle modeling with runtime system deployment. Each lineage makes tradeoffs – between usability and traceability, abstraction and implementation detail, or model richness and tooling support.

Model-Based Systems Engineering (MBSE) addresses these gaps by promoting abstraction, traceability, and change management [33]. Yet in robotics, MBSE remains underused – despite its adoption in fields like aerospace and automotive. This has led to a new class of frameworks exploring how lifecycle modeling might integrate into robotic system engineering – such as *ISE&PPOA* and *MROS*, and more recently, our own work on *MeROS*.

## Middleware / Standardization

*Formal Standardization Roots:* CORBA, RTC Some of the earliest structured approaches to robotics software emerged from general-purpose standardization efforts – especially those driven by the Object Management Group (OMG). The *Robotic Technology Component* (RTC) specification [37] built on CORBA middleware and adopted modeling formalisms like UML and IDL to define reusable, platform-independent components with well-specified execution semantics.

These standards aimed to bring rigor and portability to robotic systems through interface definitions, lifecycle control, and modular coordination. However, as noted by Henning [24], such committee-driven architectures often struggle to adapt quickly. Without feedback from daily development, standards risk becoming too rigid or complex for practical use.

Many of the original ideas – such as component roles, structured execution, and defined lifecycle states – remain influential and continue to shape current frameworks and their modular designs. The core challenge lies in balancing structure with flexibility – maintaining rigor without limiting development agility.

While CORBA's influence has waned in general software development, it remains active in certain robotics contexts – especially in real-time systems or where long-lived infrastructure persists. Platforms like *OpenRTM* and *OPRoS* are natural extensions of this lineage, whereas others such as

*Orocос* or *BCM* reflect a more selective inheritance. Our lineage grouping reflects this divergence – not by strict ancestry, but by the architectural and methodological priorities that now define these ecosystems.

*OpenRTM* *OpenRTM-aist* (Ando [2]) is a CORBA-based middleware framework developed by Japan's National Institute of Advanced Industrial Science and Technology (AIST) for component-based robotic integration. Built around the OMG RTC standard [37], it defines *RT-Components* with standardized ports, execution contexts, and lifecycle control – enabling modular reuse, introspection, and multi-language deployment. Supported by tools such as *RTBuilder* and *RT-SystemEditor*, OpenRTM remains one of the most complete realizations of the CORBA middleware vision. Variants like *RTMSafety* extend the model using SysML and IEC 61508/61499 function blocks, offering partial support for lifecycle traceability and safety assurance [23]. OpenRTM's design emphasizes platform stability and long-term maintainability, with extensions like *OpenHRP3* [30] supporting humanoid control and simulation within the same ecosystem. Its modeling capabilities and limitations are reflected in our comparative overview (Table 1).

*OPRoS* The *Open Platform for Robotic Services (OPRoS)* (Jang [29]) was a Korean government-led initiative to deliver an end-to-end software development environment for modular robotic services. Its architecture encompassed an Eclipse-based IDE, component runtime, simulator, and integrated test tooling [22]. While OProS did not adopt formal modeling languages like SysML or support layered requirement modeling, it integrated low-overhead design-time and runtime tools for component reuse, system assembly, and visual debugging. Though no longer maintained, OProS represents a national effort to promote accessible middleware tools over formal verification or model-driven workflows.

*CLARAty, SmartSoft* The Coupled Layer Architecture for Robotic Autonomy (*CLARAty*) was developed by NASA JPL to enhance modularity and cross-mission software reuse in planetary exploration [44, 36]. Its two-layer architecture separated hardware abstraction from high-level autonomy, enabling deployment across heterogeneous robotic platforms. *SmartSoft*, developed in Germany, focused on predictable component behavior through declarative coordination and service-based design [40]. While both contributed significantly to early middleware formalization, neither incorporated model-based systems engineering (MBSE) artifacts such as system traceability or requirements alignment. Their adoption remained limited – especially in settings that demanded lifecycle modeling or integration with model-based tools. For these reasons, they are not included in the central comparison table, though they remain important conceptual forerunners in the lineage of robotics software frameworks.

Collectively, these frameworks represent a phase of robotics development shaped by formal architecture and

government-driven goals, but with limited support for life-cycle modeling and validation.

## Runtime Execution

While early robotics frameworks focused on standardizing middleware and distributed interface protocols, a parallel lineage emerged in response to different pressures: real-time determinism, modularity under latency constraints, and practical deployment needs. Frameworks like *Orocos*, *GenoM*, and *BCM* were developed with embedded control in mind, prioritizing execution fidelity and reusable components over full lifecycle modeling. These architectures laid the groundwork for runtime-first software practices still relevant in field robotics and automation.

One early example was *Orca* [7], a decentralized component framework based on ICE middleware. Though now discontinued, *Orca* introduced practical ideas around compositability, interface-driven design, and transparent deployment. While it lacked support for lifecycle modeling or long-term sustainability, it helped lay groundwork for later systems such as *Orocos*.

***Orocos*** The *Open Robot Control Software (Orocos)*[10], initiated by Herman Bruyninckx, focused on deterministic scheduling, modular composition, and low-latency execution in real-time robotic systems. Its Real-Time Toolkit (RTT) enables predictable dataflow between components without layered modeling abstractions. Designed as a response to the rigidity of CORBA-based middleware, *Orocos* prioritized runtime introspection, traceability, and direct code-level reuse. Its principles later shaped model-driven efforts such as the *BRICS Component Model (BCM)*[13], extending its influence beyond runtime tooling.

***GenoM/GenoM3*** *GenoM*[1], developed at LAAS-CNRS, introduced a modular task model for embedded autonomous robots. It organized sensing, control, and decision logic into self-contained services with explicit execution control. *GenoM3*[34, 21] restructured this approach to be middleware-independent and verifiable. It supports formal model checking via Fiacre and TINA and relies on templates for code generation. Its strict handling of component interfaces and behavioral contracts supports reliable verification pipelines. While it avoids standard SysML/UML tooling, *GenoM3* defines clear service definitions tailored to real-time execution.

***BCM BRICS*** (Best Practice in Robotics) was a European initiative aimed at harmonizing robotics software through reusable, platform-independent practices [11]. Within this context, the *BRICS Component Model (BCM)* [12] introduced a formal metamodel and coordination structure to support component design across frameworks like ROS and *Orocos*. *BCM* targeted seamless integration with toolchains through model transformations and promoted model-first engineering while preserving execution semantics. Though it lacked full toolchain maturity and was discontinued after

the project, *BCM* remains an early example of combining runtime architecture with model-driven goals.

These frameworks contributed key ideas – modularity, execution control, interface clarity – that informed later MBSE-oriented platforms. *BCM*, in particular, helped bridge execution-time systems with formal design workflows, shaping the traceability and architectural rigor that characterize frameworks like *MeROS*, *MROS*, and *ISE&PPOOA*.

## Model-Driven Lifecycle

This section reviews frameworks developed to improve traceability, requirement modeling, and system abstraction in robotics software engineering

***ISE&PPOOA*** *ISE&PPOOA* is a model-based systems engineering methodology that combines breadth-first requirements modeling with layered architecture design. The method favors semi-formal diagrams and design heuristics to support modeling discipline in early system design. It extends SysML with PPOOA's port- and service-based constructs to model both software and system-level views of real-time systems. The method emphasizes functional decomposition, hierarchical refinement, and modular design of software and hardware. While it does not support executable simulation or runtime testing, it enables traceability across stakeholder goals, system functions, and implementation artifacts. It has been applied in collaborative robotics and UAV domains [20], with tool support focused on structure, reusability, and early-stage modeling discipline.

***AutomationML***, originally developed for industrial automation, has been extended to robotic domains via Semantic Web integration and code generation [25]. However, its lack of behavioral abstraction and SysML support limits its applicability in model-based system design, and it is not included in the lifecycle comparison.

***RobotML*** [18] introduced a UML-profile-based DSL for robotic system modeling, simulation, and deployment targeting multiple middleware supported by a Papyrus-based toolchain and designed for deployment across platforms such as ROS and *Orocos*. Despite a rich domain model, it remains prototypical and was not widely adopted. These frameworks highlight the variety of modeling approaches explored in robotics, but also underscore the difficulty of sustaining full lifecycle support and verification – gaps that more recent frameworks like *MeROS* aim to address.

***MROS (RobMoSys)*** *RobMoSys* was a European H2020 project promoting contract-based modeling and separation of concerns in robotics software. It introduced meta-models for roles, interfaces, and component composition, supported by tools such as SmartMDSD and Papyrus4Robotics. These enabled early-stage validation, component reuse, and structured integration workflows.

*MROS*[42], developed within this effort, extended the architecture to support runtime reconfiguration via ontological meta-control and variation point selection[5]. Demonstrations included adaptive planning and runtime monitoring [15]. While MROS provided important tooling for life-cycle modeling, it remained peripheral to mainstream ROS development. Still, its principles contributed to ongoing interest in model-centric robotics design.

*PDD Property-Driven Design (PDD)* [6] focuses on swarm robotics and uses system-level properties to guide model refinement and verification. It avoids SysML/UML and uses formal methods (e.g. checking to validate emergent behavior properties in swarm systems) with lightweight tooling. Although narrow in scope, PDD demonstrates how behavioral verification can be integrated into iterative modeling workflows – a direction MeROS generalizes.

*Positioning MeROS* MeROS does not attempt to redefine model-based robotics, but builds directly on the structure and lessons of earlier efforts. It follows a minimal, standards-aligned approach, grounded in SysML, to address a long-standing gap: linking architecture, behavior, and runtime within a traceable, verifiable V-model process. While previous frameworks introduced valuable concepts, many remained fragmented or faded from practice. MeROS stays close to ROS conventions while aiming to restore lifecycle consistency often missing from open-source workflows. It is not a reinvention, but a practical synthesis of what has proven effective.

A detailed comparison of these model-based frameworks is provided later in the paper, followed by a discussion of their tradeoffs and implications.

## 6. Discussion

### Comparison Motivation and Scope

The development of robotics software systems has followed diverging trajectories: from CORBA-based standardization, to runtime modularity frameworks prioritizing execution control, to model-driven efforts advocating for lifecycle structure. Each of these lineages has contributed essential insights – yet none have fully reconciled modularity, real-time viability, and lifecycle traceability in a unified, ROS-compatible workflow.

Rather than treating these approaches as mutually exclusive, Table 1 situates them along a common lifecycle axis – from stakeholder requirements to system-level and subsystem-level verification. This mapping reveals how core architectural priorities often resulted in blind spots: some frameworks formalized early-phase design, others focused on runtime behavior, but few connected both ends in a traceable and verifiable way.

The entries in the table are best understood broadly as design and engineering frameworks – some encompassing modeling languages, others full development toolchains

or runtime platforms. Their scope and maturity vary significantly, yet all respond to the same fundamental challenge: developing complex robotic systems that are reliable, reusable, and adaptable across contexts.

MeROS emerges within this landscape not as a disruptive alternative, but as a compositional synthesis. It had been built to accompany the operational realism of ROS, integrates formal modeling from codified MBSE practices, and proposes a lifecycle-aligned methodology that is both practical and traceable. In doing so, it aims to bridge the persistent gap between runtime infrastructure and lifecycle fidelity – without discarding the hard-won lessons of earlier frameworks. Yet while this lifecycle mapping clarifies structural trade-offs, it leaves out another class of practical questions – those related to community adoption, tooling support, and long-term maintainability. These ecosystem characteristics often determine whether even well-designed frameworks survive in the field.

Table 1 synthesizes these insights, mapping the lifecycle coverage of each framework and underscoring the methodological gaps that the MeROS ecosystem aims to address.

*Structural Coverage and Intended Usage.* Table 1 summarizes structural characteristics captured by the proposed V-Model, including traceable abstraction layers, compositional modeling, and behavioral mapping. The model accommodates both top-down architectural planning and reconstruction of legacy systems. These properties support integration across a range of engineering workflows and lifecycle phases. This articulation emphasizes validation of the V-Model’s structure within a mid-phase system context, where architecture and behavior are defined and embodied.

*Framing Key Dimensions of MBSE Maturity.* Beyond structural clarity, the MeROS ecosystem – fortified by its V-model compatibility – offers a framework to address deeper challenges that define the long-term applicability of MBSE in robotics. We identify three foundational dimensions: (1) alignment between *simulation and runtime* modeling (including digital twin capabilities), (2) *physical grounding* of behaviors in embodied environments, and (3) *compatibility with assurance* processes for certification. These elements define critical readiness checkpoints for any framework aiming to support safety-sensitive or adaptive robotic applications. The following sections examine how MeROS engages with these dimensions across the development lifecycle.

### Simulation-First Development and the Role of Continuous Modeling

Simulation has become a central asset in modern robotics development workflows. Aligned with the structure of the V-model, simulation enables parallel progress in behavior specification and validation, decoupled from hardware realization. This supports early-stage verification and also sustains runtime co-evolution via monitoring and iterative updates. Prior work in this research lineage has already

Source / Target	Code & fix	Concept plan	System reqs	System design	System V&V	Subsys reqs	Subsys design	Subsys V&V	HW reqs	HW design	HW V&V	SW reqs	SW design	SW V&V	SysML/UML
<i>ROS (ROS 2)</i>	✓	✗	✗	▲ / ✗	▲ / ✗	✗	▲	▲ / ✗	✗	✗	✗	▲ / ✗	▲	▲ / ✗	✗
<i>OpenRTM (Ando [2]; (including RTMSafety [23]))</i>	✗	✗	▲	✓	▲	▲	✓	✗	✗	✗	✗	▲	✓	✗	✓
<i>OPRoS (Jang [29])</i>	✓	✗	▲	✓	▲	▲	✓	▲	✗	✗	✗	▲	✓	▲	✗
<i>Orocos (Bruyninckx [10, 13])</i>	✓	✗	▲	▲	✗	✗	✓	✓	✓	✓	✗	✓	✓	✓	✗
<i>GenoM3 (Mallet [34])</i>	✗	✗	▲	✓	✓	✓	✓	✓	✗	✗	✗	▲	✓	✓	✗
<i>BCM (Bruyninckx [12])</i>	✗	✗	✓	✓	✗	✓	✓	✗	✗	✗	✗	▲	▲	✗	▲
<i>ISE&amp;PPOOA (Fernandez [20])</i>	✗	▲	✓	✓	▲	✓	✓	▲	✗	✗	✗	✓	✓	▲	✓
<i>MROS (Silva [42])</i>	✗	✓	✓	✓	▲	✓	✓	▲	✗	✗	✗	✓	✓	▲	✓
<i>PDD (Brambilla [6])</i>	✗	✗	✓	▲	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
<i>MeROS (Winiarski [46])</i>	✗	✓	✓	✓	✓	✓	✓	✓	✓/▲	▲	✓/▲	✓	✓	✓	✓

**Table 1**

Comparison of frameworks and methodologies for robotic systems development. Symbols: (✓) – supported, (✗) – not supported, (▲) – partial or informal support (e.g., without simulation, executable validation, or traceable test infrastructure).

demonstrated compatibility between SysML-based architectures and co-simulation infrastructures. The EARL modeling approach [49] and subsequent MeROS developments [46, 47] have shown how executable models and system-level abstractions can be integrated into simulation loops. Recent extensions to this methodology have investigated the structural and runtime consistency between simulated models and physical embodiments [19], laying groundwork for digital twin alignment. In this context, MeROS does not implement a digital twin system per se, but its support for co-simulation and architectural traceability allows for digital-twin-like workflows. HeROS, serving as a minimal but complete physical platform, enables grounded verification of these model-derived assumptions. In the current work, we focus on how this setup enables lifecycle-wide simulation alignment within a MeROS-tailored V-model framework.

### Lifecycle Traceability and Certification Readiness

Robotics systems intended for safety-sensitive domains—such as collaborative manufacturing, healthcare, or autonomous mobility—are increasingly expected to comply with structured assurance practices. These practices demand traceable development workflows and rigorous verification from high-level goals to implemented behavior.

MeROS does not prescribe a certification process, but its SysML-based modeling, modular decomposition, and requirement-to-code traceability provide a strong foundation for assurance workflows. Unlike ROS-compatible frameworks focused solely on runtime, MeROS supports top-down design and bottom-up validation—enabling model artifacts to be reused in safety-critical contexts. Projects like RTMSafety [22] highlight the difficulty of achieving certification with open-source platforms, further underscoring the significance of MeROS’s structured approach.

Beyond robotics, fields like automotive and aerospace impose even stricter lifecycle compliance. While MeROS does not replicate these domain-specific certification processes, it provides a modeling and verification scaffold compatible with their core expectations—helping systems remain auditable and verification-ready as they scale.

### From Simulation to Physical Grounding

While model-based development and simulation-first strategies enable early testing and architectural refinement, they cannot fully replace physical grounding. As Brooks observed, “The world is its own best model” [8], highlighting that real-world embodiment is the only reliable test of behavioral validity. MeROS facilitates system modeling and logic validation prior to deployment, but it is through integration with physical platforms like HeROS that these assumptions are stress-tested under real-world dynamics [48]. HeROS supports executable models derived from MeROS specifications, enabling systematic validation across sensorimotor feedback loops. This methodology was recently explored by Dudek et al. [19], who proposed SysML-derived metrics to quantify fidelity between simulated and embodied behaviors. MeROS [46] reinforces this by enforcing structural modeling constraints that preserve consistency across abstraction layers.

This process not only supports technical validation, but also epistemic assessment — confirming whether abstractions remain coherent in embodied settings. Recent work has extended this methodology with SysML-based metrics for evaluating simulation-to-physical consistency [19], while MeROS formalizations introduce explicit modeling constraints to enhance this alignment [47]. In this way, MeROS and HeROS enable a continuous loop of design, simulation, and grounded evaluation — forming a SysML-aligned lifecycle from abstract models to physical embodiment.

### Bridging Prior Work and Present Scope

The current formulation unifies two previously established directions: the metamodeling principles defined in MeROS [46] and the embodiment-focused validation enabled by the HeROS platform [48]. While this paper centers on the integrated V-model alignment, prior research has already addressed complementary aspects—such as behavioral synchronization in EARL [49], and structural consistency metrics for simulation vs. physical execution in SPSysML [19]. Certification traceability, too, has been explored through architecture-level annotations in earlier MeROS iterations.

Rather than redefining model-based systems engineering (MBSE), MeROS builds on this body of work to offer a robotics-tailored scaffolding that connects modeling, simulation, embodiment, and assurance. The V-model presented here inherits and exposes interfaces for these established assets, enabling systematic integration without demanding conceptual reinvention.

We conclude by summarizing the methodology's scope, contributions, and intended trajectory

## Conclusions

This work responds to a persistent gap in robotics engineering: the limited availability of structured, lifecycle-aware development practices within the widely adopted ROS 2 ecosystem. Rather than proposing a universal methodology, we demonstrate how a MeROS-aligned adaptation of the V-model can introduce traceability, standards-conscious modeling, and reuse-friendly structure—guiding development from early concept through simulation, integration, and validation.

Through a representative application on the *HeROS* platform, we have shown that this method applies even to heterogeneous, multi-robot systems where embodied feedback plays a key role. By aligning architectural modeling with physical embodiment and certification-aware workflows, the proposed methodology supports essential MBSE practices such as modular decomposition, co-simulation, and traceable verification—while also supporting epistemic validation under real-world dynamics.

While MeROS and its methodological framing remain under active refinement, the present results confirm that this combination can serve as a practical scaffold for projects facing both engineering complexity and assurance demands. It establishes a continuity between abstract system design and grounded robotic behavior, informed by simulation, verified in embodiment, and documented for structured development lifecycles.

This work is not offered as a complete solution, but as a useful and adaptable starting point. We invite reuse, feedback, and critical reflection—whether to build upon our assumptions or challenge them for the betterment of open robotics practice.

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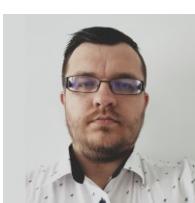
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