

Modular Mobile Intralogistics for Flexible Production in Circular Factories

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Circular production requires adaptable manufacturing and intralogistics systems capable of responding to uncertainty in the arrival, configuration, and condition of returned products and in the resulting process sequences. This paper presents the hardware implementation and operational concept of a modular intralogistics system that separates mobility from task-specific functionality. Omnidirectional mobile platforms autonomously couple to interchangeable transport and manipulator modules through a standardized mechanical and electrical interface. The platforms can transport and set down the modules, which may operate while coupled or as stationary resources. This separation allows mobile platforms and functional resources to be dimensioned and assigned independently. The system's broader flexibility is illustrated through three representative scenarios: an in-motion product handover, cooperative transport using heterogeneous mobile platforms, and a moving temporary production cell with internal material flow. To coordinate the resulting configurations, the established Omni-Curve Parameter framework is applied as a common motion interface. A desired motion specified at a common reference point is mapped to platform- and wheel-level commands while accounting for the geometry and kinematic constraints of the participating platforms.

[Keywords: circular production; flexible intralogistics; modular production systems; mobile robots; heterogeneous robot coordination; cooperative transport]

1 INTRODUCTION

Manufacturing systems are increasingly required to reduce resource consumption while retaining the value embedded in products and components. Circular production addresses

this objective by returning used products and parts to productive use through reuse, repair, refurbishment, remanufacturing, and technological upgrading [1, 2]. For returned products, however, the arrival time, configuration, and condition cannot generally be specified in advance. Moreover, the outcomes of inspection and disassembly may change the subsequently required process sequence. Industrial circular production therefore requires adaptable production resources and material-flow structures.

In this setting, intralogistics must do more than transport materials between predefined locations. It must connect changing process steps and enable products, components, and production resources to be rearranged as requirements evolve. The modular intralogistics system developed in prior work [3] separates mobility from task-specific functionality. Mobile platforms can couple to, transport, and set down self-contained functional modules. These modules may operate individually or be combined into temporary production cells that are stationary, partially mobile, or moving while operations are performed. Several platforms may also cooperate to transport products or modules that exceed the capability of a single unit.

The ability to detach the functional modules is central to the flexibility of the concept. Permanently mounting each module on a dedicated platform would bind a mobile resource to a function that may require mobility only intermittently. Interchangeable modules instead allow the numbers of mobile platforms and functional modules to be dimensioned independently. After placing a module, a platform can become available for another transport or production task. Functional resources can thus be provided where they are required without permanently assigning a mobile platform to each capability.

Coordinating the resulting configurations requires a common way of commanding their motion. Individual robot-module configurations, cooperative transport formations, and temporary production cells may differ in their

footprints, spatial arrangements, and drive kinematics. Their required relative arrangements must be maintained during coordinated motion, while the commanded motion must remain feasible for every participating platform. Some configurations additionally require individual resources to move relative to a stationary or moving formation.

The current hardware demonstrator uses homogeneous omnidirectional mobile platforms because their independent planar translation and rotation facilitate docking and coordinated operation in compact configurations. The broader concept is not restricted to this drive type, provided that the available motions and kinematic constraints of other platforms can be represented by the steering model. Building on the previously developed system, this paper presents the implemented modular hardware and illustrates the flexibility enabled by detachable functional modules through three representative operational scenarios: an in-motion product handover, cooperative transport, and a moving temporary production cell. A steering method based on Omni-Curve Parameters (OCP) is applied as a supporting capability for operating these configurations, including formations containing different drive types.

2 RELATED WORK

Research on reconfigurable production systems has produced several approaches for adapting production resources and material flow to changing requirements. Matrix production replaces fixed process sequences with flexibly linked stations and variable product routing [4]. Swarm production extends this principle by introducing movable workstations whose spatial arrangement can be changed during operation [5]. For circular production, Fleischer et al. describe adaptive production equipment and autonomous intralogistics as interacting elements of a reconfigurable production system [6]. These approaches establish the production-system context for the present work, but primarily address reconfiguration through factory structures, resource organization, and production control.

The modular intralogistics system examined here was introduced at the architectural level in [3]. In that work, mobile platforms carry self-contained functional modules, while an ontology represents their capabilities and supports knowledge-based task assignment. The same modular resources are also considered within a broader multi-agent architecture for decentralized task allocation and execution [7]. These studies provide the system-level foundation for the present paper but do not examine the physical implementation and coordinated configurations enabled by the detachable modules in detail.

Commercial systems illustrate individual aspects of this modular approach. The ConTrax system separates a robotic arm from its mobile platform by mounting it on a trans-

portable supply station. The platform can place the station, become available for other transport tasks, or operate together with it as a mobile manipulator [8]. Robotunits offers configurable AGV top modules for different transport and transfer functions [9]. These examples demonstrate the industrial relevance of separating or configuring mobile and functional resources. Their publicly documented operation, however, focuses on individual platform–payload combinations rather than coordinated multi-platform configurations forming temporary production systems.

When several functional modules operate and move as a common system, their supporting mobile platforms must coordinate their motion while maintaining the relative arrangement required by the task. The broader field of cooperative multi-robot transport and its associated coordination and control strategies is reviewed by Tuci et al. and Farivarnejad and Berman [10, 11]. For coordinating platforms with different drive kinematics, Omni-Curve Parameters provide a common representation of vehicle motion independent of a specific wheel arrangement [12]. Subsequent work derives the corresponding actuator commands and characterizes the feasible motions of different chassis configurations [13]. The approach has also been applied to decentralized cooperative transport in heterogeneous robot fleets by treating the complete transport group as a vehicle with multiple wheels [14]. The present work applies this basis to a modular production system in which the participating resources and their arrangement can change between tasks and individual resources may move relative to a formation during operation.

Against this background, this work focuses on the physical implementation and operational possibilities of the modular system. Three representative scenarios illustrate the flexibility obtained by combining detachable functional modules and mobile platforms in task-specific configurations. Resource selection and spatial arrangement are assumed to be specified beforehand. The established OCP approach is applied as a supporting method for commanding the resulting configurations, including cases in which platforms have different drive kinematics or individual resources move relative to a formation.

3 MODULAR HARDWARE ARCHITECTURE AND PROTOTYPE IMPLEMENTATION

Building on the system architecture described in [3], the hardware implementation separates mobility from task-specific functionality. Mobile platforms provide mobility and can couple to interchangeable functional modules for transport, buffering, manipulation, or other process-specific tasks. This section describes the mobile platform, the common module interface, and the two implemented module prototypes.

The mobile platform shown in Figure 1 uses a four-wheel omnidirectional drive and laser scanners for localization and navigation. A comparatively small onboard buffer battery supports short movements without a module, particularly between setting down one module and picking up another. During coupled operation, the platform is supplied by the larger batteries integrated into the module. The omnidirectional drive enables translation and rotation to be controlled independently, facilitating maneuvering and docking in confined spaces.



Figure 1: Omnidirectional mobile platform used in the current hardware demonstrator

The module dimensions and supporting structure permit docking from any of the four sides. A higher-level planning instance selects the approach side according to the current task and spatial conditions. The platform first approaches the selected side and uses the four module legs as geometric references within the laser scanner data for coarse positioning beneath the module. An upward-facing camera in the mobile platform subsequently detects AprilTag markers attached to the module underside, enabling the more accurate alignment required by the mechanical interface. Once aligned, the platform raises its lifting mechanism, causing four locating pins to enter the corresponding counterpart in the module. These pins establish a stable and reproducible mechanical connection. At the same time, electrical contacts on the platform engage with contacts on the module underside, allowing the module battery to supply the coupled system. The module can subsequently be transported or operated while attached to the platform. Lowering the lifting mechanism releases the connection and leaves the module supported by its legs, allowing the platform to proceed to another task.

Figure 2 shows the two module prototypes currently implemented. The manipulator module carries a UR10e robotic arm powered by batteries integrated into the module. When coupled to a mobile platform, the combination forms a mobile manipulator and allows manipulation capabilities to be relocated within the factory. The module can also be deposited at a suitable location and used as a temporary stationary manipulation resource. This separation avoids per-

manently assigning a mobile platform to a manipulator during operations for which mobility is not required.

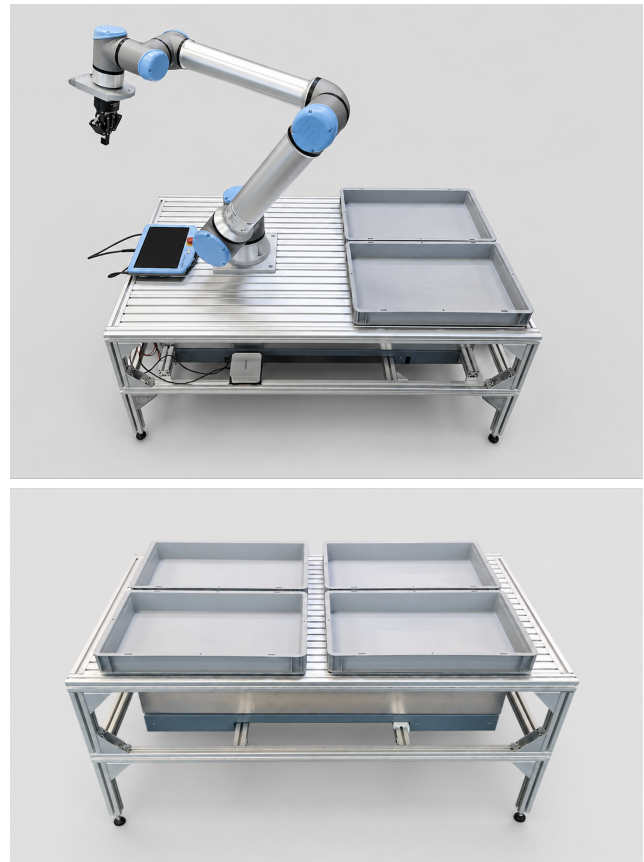


Figure 2: Implemented functional modules (top: manipulator module; bottom: transport module)

The second prototype is a transport module with a loading surface that can carry several products simultaneously. It can also serve as a temporary buffer when products are not immediately required by a subsequent process. Combining transport and buffering within one module allows product movements to be consolidated and reduces the need for immediate handovers between consecutive process steps.

The current implementation consists of homogeneous omnidirectional mobile platforms and the two presented module types with standardized geometries. Further module types considered within the broader concept and for future development include inspection modules for product analysis between process steps, storage and buffer modules for longer-term storage and product availability throughout the factory, and processing modules for operations such as disassembly or milling. Depending on the process requirements, these resources can be combined into configurations with different compositions and spatial arrangements.

The selection of the participating resources, their number, and their arrangement are assumed to be specified in advance and are not determined within this work. The following section uses three representative scenarios to illustrate the operational configurations and flexibility enabled by the separation of mobile platforms and functional modules.

4 OPERATIONAL SCENARIOS FOR COORDINATED MOTION

The modular architecture extends the capabilities of the system beyond conventional point-to-point material transport. By combining mobile platforms with functional modules, the system can transport and buffer products while also relocating process capabilities and arranging them into task-specific configurations. These configurations can cooperatively handle large products, perform manipulation and product transfers while moving, or form temporary production cells with their own internal material flow. To reflect the broader scope of the concept, the scenarios also consider functional modules and mobile platforms with drive types beyond those of the current implementation. The following three scenarios illustrate the resulting capabilities and flexibility of the modular system.

In-motion product handover

The first scenario demonstrates how transport and manipulation can be performed concurrently. A manipulator module is positioned between two transport modules and travels with them while transferring a product from one transport module to the other. Products can thereby be handed over, sorted, or reassigned during transport according to their subsequent destinations. By overlapping the manipulation with movement through the factory, the system avoids a separate stationary handover at a fixed transfer point and can reduce waiting times and additional transport movements.

Figure 3 illustrates a possible sequence of the in-motion handover. Throughout the process, the three platforms maintain a relative arrangement that keeps both transport modules within the workspace of the manipulator. This arrangement must also be preserved when the formation follows a curved trajectory, for which the required velocity of each platform depends on its position within the formation. The scenario shows how independently mobile resources can temporarily combine their capabilities to form a moving transfer station, allowing products to be handed over without interrupting their transport through the factory.

Cooperative transport with heterogeneous platforms

The second scenario illustrates how several mobile platforms can combine their transport capacities to move a

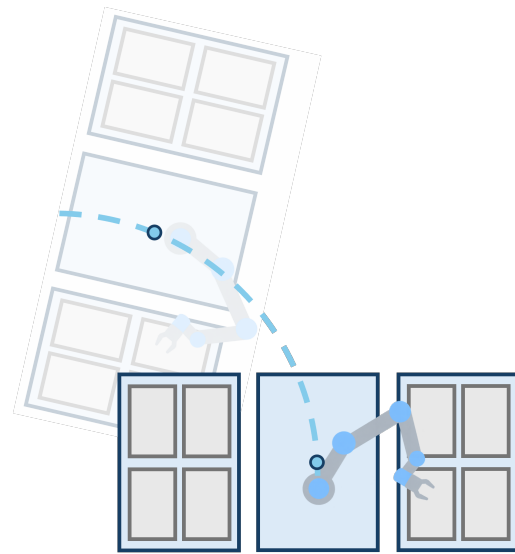


Figure 3: Conceptual sequence of an in-motion product handover between two transport modules

product that cannot be handled by a single platform because of its dimensions, geometry, or mass. The transported object may also be a functional module whose size exceeds the capacity of one mobile platform. In the triangular formation illustrated in Figure 4, one differential-drive platform supports the front of the load, while two omnidirectional platforms support the rear. The cooperative approach avoids the need for a dedicated larger vehicle and allows suitable mobile platforms available in the system to be assigned according to the properties of the load.

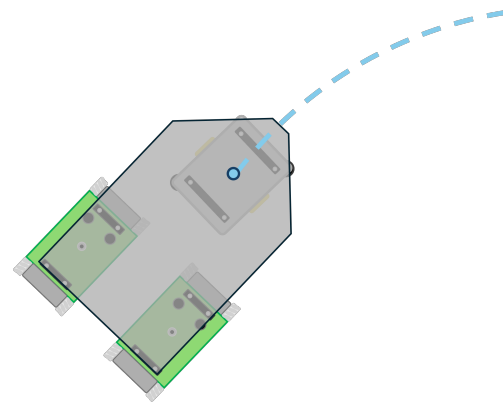


Figure 4: Cooperative transport of a large product using one differential-drive and two omnidirectional mobile platforms

Because the platforms support a common load, they must maintain their relative arrangement throughout the transport. Their individual movements must therefore corre-

spond to the same translational and rotational motion of the load while accounting for the kinematic characteristics of each drive type. This allows suitable platforms with different drive types to cooperate within the same transport configuration, increasing flexibility in resource allocation and making better use of the platforms available in the system.

Temporary production cell

The third scenario illustrates one of the most comprehensive capabilities of the modular concept: functional resources can be brought together to form a temporary production cell tailored to a previously defined process. Unlike permanently installed production structures, such a cell can be assembled where and when it is needed, adapted when the process changes, and disbanded afterward. Its resources can then be reassigned to other production or intralogistics tasks. Depending on the application, temporary cells can contain different numbers and types of modules in a wide range of spatial arrangements. They may remain stationary, move as a complete formation, or include individual resources that move relative to stationary or moving parts of the cell.

Figure 5 shows one exemplary configuration. Four modules form an L-shaped cell. A transport module buffers the products to be processed, a manipulator module transfers them to and from a disassembly module, and an inspection module analyzes selected products when required. An additional manipulator module can temporarily join the cell and move between its process units, for example to transfer selected products to the inspection module.

The configuration can be adapted to the required process sequence without permanently assigning every resource to the cell. For example, the additional manipulator is needed only when products must be transferred to the inspection module and can otherwise support another task. This task-specific allocation enables production capabilities to be provided where they are currently needed and can improve the utilization of mobile platforms and functional modules.

In the illustrated scenario, the L-shaped core moves along a path while selected processing and handling operations continue. Production, internal material transfer, and relocation can therefore overlap instead of being performed as separate consecutive steps. The concept thereby combines a flexible production structure with mobile process execution and an adaptable internal material flow.

While the four core modules preserve their relative arrangement, the additional manipulator moves between transfer positions defined relative to the cell. It must therefore follow the overall motion of the cell while simultaneously moving within it. Together, the three scenarios illustrate how the modular system can combine resources for in-motion product handovers, cooperative transport, and tem-

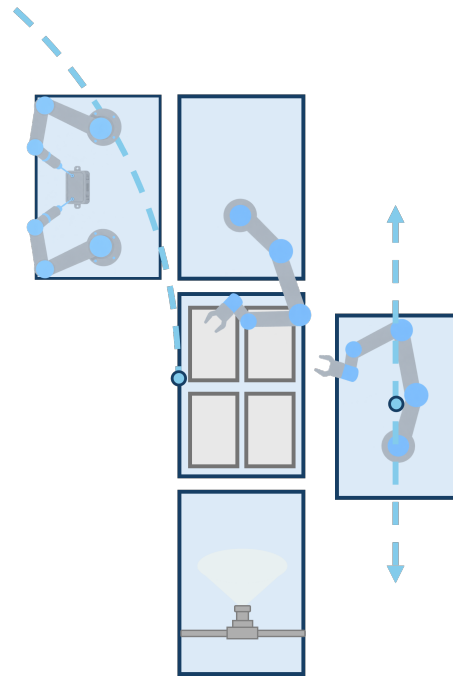


Figure 5: Conceptual illustration of a moving L-shaped temporary production cell with an additional manipulator module performing internal product transfers

porary production cells. Although these applications serve different purposes, they all require multiple mobile platforms to move in coordinated formations, in some cases while individual resources also move within them. The following section presents the OCP-based steering method used to describe and command the required formation-level and relative motions.

5 OCP-BASED COORDINATION OF MODULAR CONFIGURATIONS

The configurations introduced in the previous section require a common motion description for groups that can differ in their composition, geometry, and drive kinematics. This section therefore applies the established Omni-Curve Parameter framework to the modular configurations considered in this paper rather than introducing a new steering formalism. The adopted architecture separates the desired motion of the overall formation from the inverse kinematics of the participating platforms. A common motion is specified at a reference point, while the corresponding platform and wheel commands are derived according to the geometry and kinematic constraints of the current configuration.

5.1 Kinematic Coordination of the Wheels

An OCP command describes the motion at a reference point K using the nominal velocity v_n , nominal curvature κ_n , and slip angle β . The nominal velocity is scaled according to

$$v_s = v_n v_{\max}, \quad (1)$$

where $v_{\max}$ is the maximum velocity defined for the platform or configuration. The slip angle β describes the direction of the velocity vector at K relative to the positive x -axis of the formation coordinate system.[13]

The dimensionless nominal curvature $\kappa_n \in [-2, 2]$ describes the relation between translational and rotational motion. For $|\kappa_n| < 1$, the physical curvature is given by

$$\kappa = \kappa_n \kappa_g, \quad (2)$$

where κ_g denotes the limit curvature. For $1 \leq |\kappa_n| \leq 2$, the corresponding signed radius is

$$R = \frac{2 \operatorname{sgn}(\kappa_n) - \kappa_n}{\kappa_g}. \quad (3)$$

[13]

Based on the wheel-level mapping presented in [13], the resulting rolling velocity u_i of wheel i is given by:

$$u_i = \begin{cases} v_s \sqrt{*} & |\kappa_n| < 1 \\ v_s \kappa_g \sqrt{*} & |\kappa_n| \geq 1 \end{cases} \quad (4)$$

where v_s is the scaled speed introduced above. The wheel-dependent term $\sqrt{*}$ is defined as:

$$\sqrt{*} = \begin{cases} \sqrt{1 + \kappa^2 \vec{w}_i^2 + 2 \kappa f_i} & |\kappa_n| < 1 \\ \sqrt{R^2 + \vec{w}_i^2 + 2 R f_i} & |\kappa_n| \geq 1 \end{cases} \quad (5)$$

where R is the signed radius and $\vec{w}_i$ is the position vector from the reference point K to wheel i . The auxiliary quantity f_i is defined as:

$$f_i = \vec{w}_i^T \begin{bmatrix} \sin(\beta) \\ -\cos(\beta) \end{bmatrix} \quad (6)$$

where β denotes the slip angle. The direction factor s_i is defined as

$$s_i = \operatorname{sgn}(\kappa_n) \operatorname{sgn} \left(\vec{w}_i^T \begin{bmatrix} \cos(\beta) \\ \sin(\beta) \end{bmatrix} \right). \quad (7)$$

The required steering angle α_i of a steerable wheel i is then given by:

$$\alpha_i = \begin{cases} \beta + s_i \arccos \left(\frac{1 + \kappa f_i}{\sqrt{*}} \right) & |\kappa_n| < 1 \\ \beta + s_i \arccos \left(\frac{|R| + \operatorname{sgn}(\kappa_n) f_i}{\sqrt{*}} \right) & |\kappa_n| \geq 1 \end{cases} \quad (8)$$

If the calculated steering angle lies outside the interval $\alpha_i \in [-180^\circ, 180^\circ]$, it is shifted by $\pm 360^\circ$ to obtain the equivalent angle within this interval.

The equations provide a kinematic transformation from a common formation command to the wheel-level commands of the participating platforms. Mechanical steering limits, maximum wheel velocities, and other configuration-specific constraints can subsequently be used to determine whether the commanded motion is feasible for every platform. [13]

For a formation in which the participating platforms maintain their relative arrangement, the complete group can be represented as a single vehicle whose wheels are expressed relative to a common reference point K [14]. When the participating platforms or their arrangement changes, the wheel-position vectors and applicable kinematic constraints are updated. The same OCP representation can then be used.

5.2 Application to the Operational Scenarios

In-motion product handover. In the first scenario, the three robot-module configurations form a temporary formation in which their relative arrangement is maintained, with the manipulator positioned between the two transport modules. A reference point K is assigned to the formation, and its desired motion is expressed through (v_n, κ_n, β) . The wheel velocities and, where applicable, steering angles are obtained from Equations 4 and 8. The manipulator motion can be controlled independently while the mobile platforms maintain the arrangement required to keep both transport modules within its workspace. This operation depends on the platform controllers providing the positioning accuracy required by the manipulation task. After the handover, the temporary formation can be dissolved, and each platform can again be commanded independently using its own reference point and kinematic model.

Cooperative transport with heterogeneous platforms. The second scenario applies the same representation to the heterogeneous transport formation shown in Figure 6. The complete group is treated as one virtual vehicle, although its front and rear platforms use different drive kinematics.

The reference point K is located at the midpoint of the two non-steered wheels of the differential-drive platform. Because this platform cannot move laterally, its kinematics constrain the slip angle to $\beta = 0$. The nominal velocity v_n and nominal curvature κ_n specify the translational and rotational motion of the complete transport group. The rolling velocities u_1 and u_2 of the front platform are calculated using Equation 4. The vectors $\vec{w}_i$ describe the positions of the individual wheels relative to K . For the two rear Mecanum-wheel platforms, the motion induced at their respective platform reference points is converted into the wheel velocities u_i using their inverse kinematics.

All wheel commands therefore correspond to the same motion of the transported load, despite the different drive

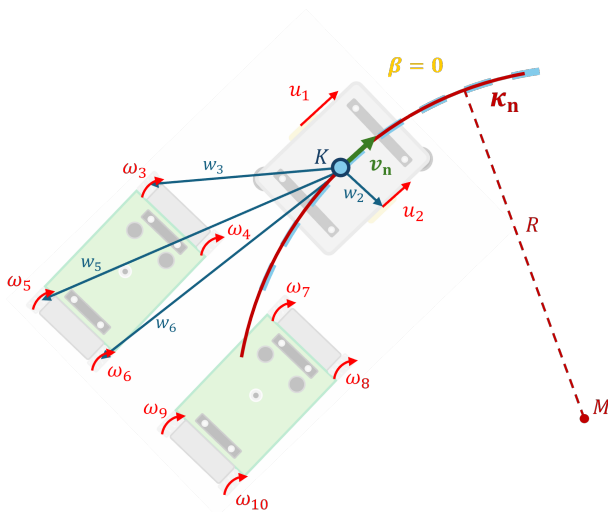


Figure 6: OCP representation of cooperative transport using one differential-drive and two Mecanum-wheel platforms. The group motion is specified at reference point K . Wheel-position vectors are shown in blue and green, while the resulting wheel commands are shown in red.

types. The admissible motion of the complete group is restricted to commands that are feasible for every participating platform. In this example, the differential-drive platform imposes the strongest directional constraint, while the Mecanum-wheel platforms adapt their individual wheel velocities to the resulting formation motion.

Temporary production cell. In the third scenario, the four platforms forming the L-shaped production cell maintain a fixed relative arrangement and are commanded using a common OCP reference point. The additional manipulator platform is not part of this fixed formation because it moves between transfer positions defined relative to the cell.

The desired global motion of this platform combines two components: the motion induced by the translation and rotation of the cell at its current relative position, and its commanded motion between the transfer positions within the cell. The resulting global platform motion is converted into an OCP command and subsequently into its wheel-level actuator commands. The additional platform can therefore remain synchronized with the moving cell while changing its position relative to the core formation.

The three applications use the same established OCP basis at different levels: as a common command for a rigid homogeneous formation, as a shared motion representation for a heterogeneous transport group, and as a means of combining formation motion with relative motion inside a temporary production cell. Once the participating resources, their spatial arrangement, and the process sequence have been specified, OCP-based coordination provides a common mo-

tion interface for operating the resulting modular configuration.

6 CONCLUSION AND OUTLOOK

Building on the previously developed system architecture, this paper presented the physical implementation and operational concept of a modular intralogistics system for flexible production in circular factories. The implemented system separates mobility from task-specific functionality through omnidirectional mobile platforms, a standardized mechanical and electrical interface, and interchangeable transport and manipulator modules. Mobile platforms can autonomously couple to, transport, and set down these modules, which can be operated while coupled or as stationary resources. This separation allows mobile platforms and functional modules to be dimensioned and assigned independently and avoids permanently binding a mobile platform to a function that requires mobility only intermittently.

Three representative scenarios illustrated how the modular architecture can support an in-motion product handover, cooperative transport using platforms with different drive kinematics, and a moving temporary production cell with its own internal material flow. These scenarios extend beyond the current demonstrator and serve as application cases for identifying the configurations and coordination requirements enabled by the modular concept. The established OCP framework was applied as a common motion interface for these configurations. It can support formations with different compositions and drive kinematics once the participating resources and their spatial arrangement have been specified.

Future work will expand the hardware demonstrator with additional functional modules, e.g., modules for inspection, storage, and buffering. This will allow the proposed scenarios to be implemented and evaluated under representative operating conditions. In addition, the synchronization of cooperating resources and the additional coordination challenges associated with temporary production cells will be investigated.

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