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Heavy-Duty Conveyor Modules for Safe Interaction between People, Forklift Vehicles and Goods in Intralogistics

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As technical developments in intralogistics continue to advance, the production efficiency of large corporations and companies is also increasing. Their warehouses are becoming increasingly fully automated, while small and medium-sized enterprises (SMEs) are still heavily reliant on manual intralogistics processes. To enable SMEs to remain competitive, this research is directed towards a multidirectional heavy-duty conveyor module that is designed to support warehouse staff by automatically moving goods across the warehouse floor in parallel with existing operations. Individual modules should function by means of plug-and-play to allow the simplest possible integration and maintenance. In addition to mechanical load requirements for individual modules, a further challenge lies in path planning and control to ensure an efficiently and collision-free operation of the collective modular floor. Therefore, two questions will be answered in this paper: First, how does such a modular tile look like and what does it consist of? Second, what must the overall control concept look like in order to achieve an increase in efficiency for SMEs?
In this paper a mechanical concept for an innovative new modular transport method for warehouse settings is presented. Additionally, the corresponding control concept is derived. Key factors to consider in the development of the mechanical part are the method of transportation with a limited budget such that an SME is able to profit off of it. Furthermore, the module is tasked with transporting goods weighting a couple of tons and enduring weights of loaded forklifts when not being used actively, thus enabling a restrictive-free floor where workers and forklifts can operate freely. To guarantee the latter part the controlling system must be able to avoid collisions with humans and other goods while still performing their own tasks. At the end of this paper the concept of a promising heavy-duty conveyor module with a corresponding movement algorithm is achieved.

[Keywords: Heavy-Duty Conveyor Module, Intralogistics, Conceptual Design, Movement Algorithm, Human-Machine-Operation]

1 INTRODUCTION

Intralogistics is subject to increasing adaptive pressure: volatile demand, shorter product life cycles, space limitations and heightened safety requirements in the interaction between people, forklifts and goods. This contribution explicitly focuses on piece-good transport. Classical stationary conveyor technology provides high throughput but is layout-bound and fixes the material flow early. Mobile systems such as AGVs and AMRs increase flexibility, but in the heavy-duty sector and for flush floor integration they frequently reach limits. A central deficit of prevalent continuous conveyors (roller, chain and belt conveyors) is their directional binding: conveying is fundamentally along a defined axis. Every change of direction requires additional aggregates such as turntables, transfers, cross shuttles or crossings — with consequences for footprint, complexity, maintenance and safety. Planar movements of piece goods are thus achieved only via nested line networks, not directly on the surface.
Against this background, the research addresses the gap between rigid line conveyors and autonomous single vehicles: sought is a modular, surface-capable heavy-duty conveyor system that can move piece goods directly, be integrated flush with the floor and remain walkable/drivable by people and forklifts. The core idea is a multidirectional drive module that enables free trajectory choice on the surface and performs direction changes without additional aggregates. Routing freedom, scalable buffer areas and easy re-configurations result — properties that make the proposed system attractive compared with existing solutions.

The goals of the paper are: (i) to derive application-oriented requirements and typical operating conditions for the transport system as well as the algorithm, (ii) to perform a systematic concept comparison following VDI 2225 to justify the selection of a preferred drive concept for subsequent development and (iii) develope a basic control scheme that can satisfy all requirements with the potential of optimization in subsequent development.

Structure of the paper: Section 2 presents the state of the art of control concepts within intralogistic settings and fundamental motion types with an explicit discussion of directional binding. At the end of it the research gap is derived and the intention of this paper os presented. Section 3 derives requirements for mechanics which will be taken into account in section 4 which introduces several conveyor concepts, evaluates them, and justifies the choice for a modular heavy-duty conveyor module. After this, section 5 defines the requirements for the control system from which a conceptual algorithm is derived and presented. This paper concludes with a summary and an outlook of future steps in the development of the modular heavy-duty conveyor and its control system.

2 State of the Art

In this section, intralogistic piece-good transport is structured by fundamental motion types. Continuous, discontinuous and hybrid systems are considered. The analysis examines how direction changes are provided and whether free, multidirectional planar motion is achieved. From this classification the fundamental elements are derived and evaluated with respect to multidirectionality and surface utilisation.

2.1 Motion Types in Intralogistics

System classes are first delineated. Continuous transport denotes a continuous material flow along defined routes. Discontinuous transport denotes event- or takt-based motion in which piece goods are gripped, displaced or set down. Hybrid systems combine both principles by coupling continuous conveying with discrete functions for direction change or alignment [1, 2].

Linear conveying is considered the fundamental translational motion along a preset line. In most manifestations a preferred direction is defined, while direction changes are provided by additional aggregates. Consequently, the layout is fixed early, modifications become more complex and buffer areas are used linearly rather than as surfaces [3, 1, 2].

Lateral transfer denotes a sideways displacement between parallel lines. In practice this is predominantly discrete, often with separate mechanisms. Additional installation space is required, transfer edges arise and the material flow is interrupted in segments [3, 4, 1, 2].

Turning and alignment serve to change the orientation of the piece good. This function is realised at dedicated stations, which requires safety distances and introduces joints or edges. Continuous planar motion is interrupted at these points [3, 1, 2].

Free multidirectional planar motion is understood as translational motion in arbitrary directions where direction changes occur without separate stations. In stationary systems this behaviour is rarely achieved; existing approaches remain predominantly line- or station-bound. Where free multidirectionality is provided, routing freedom, facilitated planar buffering and easier re-configuration result [5, 6, 2].

2.2 Basic Elements of Intralogistics

Based on the above distinction, three groups are considered: continuous conveyors (continuous flow along defined axes), discontinuous conveyors (discrete, freely manoeuvrable transports) and hybrid systems (combinations with integrated transfer functions or cellular surfaces). Selection is chiefly governed by load spectrum, required directionality, takt requirements and the degree of layout integration [3]. Suitability is decisively determined by the load carrier. Carriers with closed, smooth undersides — such as many small load carriers or closed trays — favour uniform and safe running on belt- or roller-based systems. Segmented or open undersides, as with mesh containers or pallets, require larger support spans and lead to joint crossings at transitions, which may necessitate additional transfer or alignment operations. The Euro-pallet is established in in-plant heavy-duty transport. It combines high load capacity with standardised dimensions and is compatible with a wide range of automated and manual conveyor systems; it is therefore used below as the reference load carrier for the heavy-duty sector [1, 2].

2.2.1 Examples of Continuous Conveyors

Swivelling roller (ejection/distribution module)

Swivelling-roller or pop-up modules are integrated units within roller or belt systems that selectively deflect piece goods from a continuous flow. Reject rollers located between carrying rollers are raised or rotated electrically or pneumatically and deflect the goods transverse to the main direction of travel. For pallets, suitability depends on the design of the carrying roller conveyor. The motion on module level is functionally bidirectional, since a linear main flow is combined with a transverse ejection. Advantages are precise single-item handling and good retrofit capability. Disadvantages are additional installation space, more moving parts with corresponding maintenance demand and an overall topology that remains line-bound [3, 1, 2].

Roller Conveyors

Roller conveyors are the most widespread line conveyor type for piece goods. Driven or gravity-based sections convey continuously via rows of carrying rollers. Load capacity ranges from light containers to pallet-capable heavy duty, depending on roller diameter, roller spacing, substructure and drive power. Motion is continuous and unidirectional; direction changes require separate aggregates such as turntables, lateral transfers or ninety-degree converters. Advantages are high availability, robust design and good scalability. Disadvantages are layout binding with transfer edges and additional integration effort for direction changes [3, 1, 2].

Belt Conveyors
Belt conveyors use a circulating closed support surface and are suitable for sensitive, unstable or small goods. Curves and inclined sections are possible. Typically, light to medium loads are handled; for high pallet loads, roller or chain solutions are more common in practice. Motion is continuous and unidirectional; curves are direction-guided. Advantages are gentle and quiet transport and the closed surface. Disadvantages are belt wear and cleaning effort as well as the need for additional aggregates for direction changes and transfers [3, 1, 2].

Chain Conveyors
Chain conveyors are multi-strand, form-stable line conveyors suited to harsh environments and defined driver points. Load capacity extends into the heavy-duty range; pallet- and steel-beam-capable variants are common. Motion is continuous and unidirectional; direction changes are realised via transfers or turntables. Advantages are high load capacity and comparatively low sensitivity to contamination. Disadvantages are a fixed line guidance and the need for additional aggregates for direction changes [3, 1, 2].

Gear Conveyors
Gear-based conveyors move load carriers by positive engagement via profiled drivers or teeth and thus achieve high repeatability and positional accuracy. Depending on the design, medium to high loads are possible. Motion is continuous and unidirectional; multidirectionality is not envisaged. Advantages are exact positioning capability. Disadvantages are special load carriers, lower flexibility and higher adaptation effort in case of changes [3].

Ball Conveyors
Ball conveyors consist of surface-arranged, freely rotating balls that allow displacement and alignment in arbitrary directions, typically at transfer points or manual buffer areas. Usually light to medium loads are handled; heavy duty is only reasonable in special designs. Motion is in principle multidirectional but in practice predominantly discontinuous, since ball tables are rarely driven. Advantages are high freedom of movement in a small space. Disadvantages are predominantly manual use, load limits and the absence of continuous planar conveying [3, 7, 1, 2].

2.2.2 Examples of Discontinuous Conveyors

Forklift Vehicles
Forklift trucks are manually or electrically operated transport means with high freedom of movement that pick up and set down loads between points. Load capacities range from a few hundred kilograms to several tonnes depending on vehicle class. Motion is freely multidirectional, but conveying is discontinuous in discrete travel and deposit operations. Advantages are high flexibility and area-wide use. Disadvantages are staffing, safety distances and potential route conflicts and accumulation edges [3, 1, 2].

Automated Guided Vehicles
Automated guided vehicles follow defined routes based on lines, markers or laser reflectors and achieve high repeatability with safe coexistence. Depending on platform, loads up to the tonne range are possible. The direction of motion can be changed by driving manoeuvres; conveying remains discontinuous. Advantages are plannable availability and process reliability. Disadvantages are limited route flexibility and transfers/buffers only at defined points. For lateral motion without swivelling, omni and Mecanum wheels are used in places; they increase manoeuvrability but entail higher component and integration costs and higher maintenance, and are often load-limited per wheel [8, 9, 10, 11, 12].

Autonomous Mobile Robots
Autonomous mobile robots use environment-adaptive navigation and plan paths dynamically without hard-wired routes. Typically, light to medium loads are transported; heavy-duty AMRs exist but require special superstructures. Motion is freely multidirectional; conveying is discontinuous. Omni/Mecanum wheels are used to realise free multidirectionality; the gain in mobility comes with significantly higher procurement and maintenance costs and requires very homogeneous, smooth floors. In heavy-duty scenarios, high-capacity variants are technically complex and expensive [8, 9, 10, 11, 12].

2.2.3 Examples of Hybrid Systems

Cellular Omni-Conveying Surfaces
Cellular conveying surfaces consist of hexagonally arranged, motorised cells with omni or skewed rollers. By targeted control, planar trajectories for conveying, sorting and alignment can be generated without turntables. Loads range from light to medium goods such as parcels or bins. Motion is continuous and multidirectional. Advantages are true planar motion and compact layouts. Disadvantages are load limits and only limited suitability for pallets and heavy duty [5, 7, 13, 14, 15].

Modular Roller Conveyor Systems with Integrated Cross Belts and Lifts
In these systems, roller sections are combined with cross belts, lifts and switches so that orthogonal transfers within a line-shaped network are possible. Load capacities are medium to high; pallet-capable variants are available depending on module. The main flow is continuous and unidirectional; direction changes are pos-

sible at points and act functionally bidirectionally on segments. Advantages are flexible configuration and low additional floor space. Disadvantages are a largely line-bound topology and the absence of true free planar conveying [3, 1, 2, 16, 15].

Lift-Belt Divert Modules
Lift-belt modules raise the goods and eject them laterally by belts from the main stream. Load capacities are for light to medium goods with high takt frequency. The main flow is continuous and unidirectional; lateral motion is discontinuous. Advantages are precise and fast ejection. Disadvantages are additional mechanical effort and maintenance demand as well as the absence of free planar conveying [3, 16, 15].

2.3 HIERARCHICAL STRUCTURES AND ALGORITHMIC

Currently, the trend in modern warehouses tends to operate with automatize robot fleets, whereas the front-runner is Amazon with their own development team in Amazon Robotics LLC (formerly known as Kiva Systems) and its over one million robots strong fleet across the globe. [17] To coordinate such fleets a traditional centralized approach reaches its limits fast as the main issue with it is the inability to keep computational times with increasing amounts of agents within the system and the complexity of the environment. In a review of multi-AGVs management systems ([18]) one key insight is the recommendation of focusing more on decentralized approaches as they not just distribute computational power better but also decrease the algorithm's complexity.

As it turns out for most applications it is more efficient (at least in terms of scalability) to let each agent calculated their own actions by using only local information and communicate with other agents to complete their assigned tasks. These decentralized approaches consequently require sophisticated algorithms that fit the task, use the available information and surroundings. This area of robotics is called swarm robotics whereas most of its algorithms are inspired by swarms (or colonies) in nature like bees or ants. The underlying principle is that a single agent within the swarm acts on simple rules resulting in a complex swarm behavior. [19] This is the reason why decentralized approaches simplify algorithms but they come with their own challenges. In [20] a scenario is tackled where motion and communication uncertainties are considered in the design as those are problems that can occur in real applications and potentially disrupt the whole system. Furthermore, as in most other fields, AI is a central topic of research for warehouse operation. It is applied to decision making of task allocation [21, 22], the robots' movement to increase traffic flow of the fleet [23] and swarm algorithms [24].

Another important aspect to consider is the safety of humans, goods, and machinery in this research. In traditional approaches humans and machines would be separated through fences or barriers of some sorts to prevent any interactions. In recent years however, with the increasing need of automation more and more scenarios appeared that required human-machine-interaction (HMI) and hence the need for research in that area arose. For warehouse settings the big challenge lies in the detection and prediction of human movement and the AVGs' corresponding reactions to it while still performing their own tasks (efficiently). In [25] a centralized approach is presented that tries to predict all trajectories the human workers want to take by applying the Bayesian theory of mind and from that calculate the trajectories of all operating agents. Since humans can deviate from those paths for a number of reasons an additional system is implemented that tracks the humans position in relation to the predicted state and adjusts the humans' trajectory if necessary and potentially the agents' as well. If a collision is predicted the agent is supposed to either stop or make way for the human as an emergency solution. A big downside to this approach is its need for a centralized computational unit which does not scale well with the amount of agents, humans and complex environments. Another decentralized approach is presented in [26]. Their approach takes on control barrier functions (CBF) which put constraints on a system's inputs to prevent entering hazardous areas (like collision areas) based on the current obstacles' positions and the system's dynamics. Here, the CBFs are not calculated but learned through specifically created data sets. It is then implemented as a local planner into the agents to guarantee safety. The trained neural network operates offline and can therefore not learn any further, meaning it cannot adept to changes in its environment. This is a highly mathematical framework that requires expert knowledge to design, acquire meaningful datasets and train the agents.

2.4 RESEARCH GAP

The preceding systematics shows a gap between line-bound continuous conveyors and mobile, discontinuous transport systems. Line conveyors are established in the heavy-duty sector but remain generally unidirectional; direction changes are realised at stations or with additional aggregates and interrupt planar motion. Mobile systems such as AGVs and AMRs are maneuverable in multiple directions but provide transport discretely and require transfer or buffer stations. Hybrid and cellular conveying surfaces enable continuous multidirectionality but are currently mostly limited to light to medium loads. At the same time, planar buffer functions and targeted ejection are mostly provided only in sections in today's layouts, creating additional transfer edges. For high system availability, traversability by forklifts as a manual fallback is also desirable, which existing solutions rarely fulfil.

While modular concepts are increasingly established in light-duty conveying, a modular, surface-capable system for automated heavy-duty transport that meets the specific requirements of intralogistics is still lacking. Existing solutions often rely on stationary conveyor lines with limited mobility or on autonomous single vehicles which, although flexible, remain limited in load capacity, freedom of movement and integrability.

The analysis of technical requirements shows: for in-plant heavy-duty transport with standardized load carriers — especially Euro-pallets — a system is required that moves high loads reliably (e.g. pallets up to 1,500 kg), is mobile enough for compact, modular warehouse layouts, can be integrated flush into work environments, and is easily scalable and retrofittable. At the same time, the surface should remain drivable, e.g., for forklifts up to 3,500 kg gross weight, so that manual intervention is possible in case of disturbances and operation does not come to a complete halt.

This gap is addressed by developing a modular heavy-duty pallet conveyor module that enables multidirectional motions on flush, matrix-like surfaces and is specifically designed for transporting Euro-pallets. The aim is a solution particularly accessible to small and medium-sized enterprises that can be integrated into existing production and logistics environments without high investment or adaptation costs.

In current control settings a clear shift towards decentralized, AI-enhanced transport systems capable of operating in dynamic environments when it comes to operating alongside human workers can be observed. While current research offers promising strategies for scalability, coordination, and safety, many of these approaches either rely on assumptions that are difficult to guarantee in real-world scenarios (such as perfect communication) or on lots of data to train AI models. Furthermore, the integration of human-machine-interaction into decentralized, flexible transport architectures remains an open challenge, especially in SME contexts, where cost, space, and adaptability are critical. These challenges form the foundation for the approach proposed in this work: a modular, tile-based transport system that emphasizes plug-and-play scalability, decentralized intelligence, and safe coexistence with human operators.

3 Requirements of the Transport System

3.1 Fundamental Requirements for Conveyor Systems

Intralogistic conveyor systems play a central role in organising in-plant material flows. To fulfil this role, they must meet a variety of technical, functional and integrative requirements, such as those described in ISO 3691-4:2020. In principle, a conveyor system shall be able to:

- move goods continuously or discretely along a defined route,
- perform lateral displacements between parallel tracks or positions,
- integrate turning and alignment operations into the material flow,
- enable free multidirectional movements on a surface without separate stations,
- provide targeted in-feeding and out-feeding, e.g., for sorting or order picking,
- merge multiple goods into a buffer or separate existing buffers into single units,
- integrate modularly into existing plant structures — mechanically and in control.

In addition, scalability, maintainability and energy efficiency are gaining importance — particularly in dynamic production environments where systems must be adapted flexibly to changing requirements [1, 2, 15, 6, 13, 14, 9, 10].

3.2 Specific Requirements for Heavy-Duty Conveyor Systems

For the definition of concrete requirements for heavy-duty conveyor systems, a look at the load carriers used in practice is essential. The Euro-pallet (1,200 × 800 mm) is made of wood, reusable and — depending on application and design — can carry up to 1,500 kg dynamically and over 4,000 kg statically. It is the most widespread and standardised load carrier, robust and integrable into existing racking, conveyor and loading infrastructure. It offers sufficient under-ride and gripping options for classical and automated handling equipment and, due to its standardisation, is also usable internationally . It should therefore be considered the central reference carrier in the development of future automated heavy-duty conveyor systems[1, 2, 27, 8, 16].

3.3 Requirements for Heavy-Duty Pallete Transport

Based on the general functions and requirements of an intralogistic system and the properties of the Euro-pallet, the following specific requirements arise for a modular heavy-duty pallet conveyor module:

Mechanical Load Capacity and Robustness
Systems shall be capable of carrying large weights over defined periods without suffering structural damage. Not only the maximum load is decisive, but also the load due to local peaks, vibrations or asymmetrical distributions. This places requirements on material selection, welds, bearing technology and fasteners [1, 2, 27].

Mobility and Flexibility
Depending on the application, a high degree of freedom of movement is required. While linear conveyor technologies suffice for firmly defined processes, multidirectional or omni-directional systems are increasingly necessary in more dynamic environments—such as matrix warehouses or assemblies with many material flows. This results in the requirement that directions of motion be adapted situationally—either through mechani-

cal drive solutions or through intelligent arrangement of modular elements [8, 5, 7].

Integration into Existing Infrastructures
Many industrial environments are spatially constrained or historically grown. Systems should therefore be flush with the floor, compact and retrofittable so that integration is possible without major structural modifications. Concretely, this means low build height, load capacity in the embedded state, and connectivity to adjacent modules or systems [1, 2].

Scalability and Modularity
Modern production and warehousing processes are rarely static. Systems must be capable of growing or being dismantled—whether due to changes in area, production changeovers or temporary bottlenecks. Modular concepts with standardised interfaces, defined geometries and combinable functional units provide clear added value [3, 1, 2, 16].

Maintainability and Energy Efficiency
An interrupted material flow directly affects productivity in many operations. Systems shall therefore be designed for durability, maintainability and resistance to disturbances. Energy efficiency is also gaining in importance—for ecological as well as economic reasons. Systems with reduced self-consumption, standby functionality or intelligent control contribute to sustainability [1, 2].

Economic Framework
The present module is developed as a prototype. For concept selection and subsequent assessment, a target budget per module of €40,000 is assumed (excluding installation, peripherals and structural adaptations). This cost framework serves as a boundary condition for variant comparison and economic considerations. For later series production, scaling effects are expected. As a guideline, a cost reduction factor of approximately 0.3 is assumed; the series module would thus be around 30% of the prototype price (for the same functional requirements and economical lot sizes)[1].

4 CONCEPT COMPARISON AND SELECTION

After the technical foundations have been presented in the prior sections and the research gap identified, this one introduces several suitable conveyor concepts and evaluates their suitability for use in the modular heavy-duty pallet conveyor module. To arrive systematically at robust variants from the broad solution space, the target system is decomposed into elementary functions and represented as a morphological box in Table 1. The three functional axes structure the solution space:

- Component for moving the load: gear, roller, ball, Mecanum wheel, omni wheel, conveyor belt.
- Rotation or multidirectional motion: arrangement in longitudinal/transverse orientation, swivelling, differential speed, swivelling under-belt.
- Traversability: drivable additional load carrier, retractable conveyor with closure, liftable floor with closure, directly drive-over (flush).

From the combinations of these characteristics numerous solution paths emerge. The boundary conditions of the application narrow the search space. On this basis, five concept families were identified, which are introduced, described and evaluated below.

4.1 PRESENTATION OF DIFFERENT CONVEYOR CONCEPTS

For orientation, the selected concept families are summarised here; they are then presented in detail in the subsections:

- Ball-and-gear drive
- Ball drive with rotatable drive belt
- Omni-wheel drive
- Mecanum-wheel drive

Function/Solution	1	2	3	4	5
Component for moving the load	Gear	Roller	Ball	Mecanum Wheel	Omni Wheel
Rotation or multi-directional motion	Arrangement in Longitudinal / Transverse Orientation	Swivelling	Differential Speed	Swivelling Under-Belt	
Traversability	Drivable Additional Load Carrier	Retractable Conveyor with Closure	Liftable Floor with Closure		

Table 1: Morphological box

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- Swivelling roller

The basic components of intralogistic conveyor technology described in the state of the art form the starting point for concept development. On the basis of these established designs and functional principles, the drive concepts presented below were derived and designed for use in a modular, multidirectional heavy-duty conveyor system. The aim was to translate the criteria derived from the motion requirements and the special requirements of the heavy-duty sector into viable technical solution approaches.

Ball-and-Gear-Drive
The ball-and-gear drive is a combination of a gear drive and a carpet of rollers/balls (see Figure 2). The system consists of several gears arranged in both longitudinal and transverse directions as well as a matrix of ball rollers. While the gears are responsible for active motion, the ball rollers provide passive guidance of the goods. Transport takes place on a specially adapted load carrier with a toothed profile on the underside. This profile meshes with the gears below and enables omni-directional motion. The functional principle is oriented toward existing systems such as the Festo MotionCube [7, 6, 15].

Ball Drive with Rotatable Traction Belt
This concept is based on a large number of freely movable balls, known from the cargo-floor principle (see Figure 1). The balls are set in motion from below by a swivelling drive belt via frictional contact. By targeted rotation and swivelling of the belt, the direction of traction transmitted to the balls—and thus to the goods—can be influenced multidirectionally. The load is placed directly on the carpet of rollers, while the drive belt below provides the driving force. Roller carpets and drive belts are widespread in logistics, but the combined application of these two components has not yet been found [28, 7, 15].

Omni-Wheel Drive
An omni-wheel drive is a drive system with non-swivelling but laterally rolling wheels that enables full mobility in all directions as well as rotation about the own axis. In the simplest variant, three wheels are arranged in a circle, whose rotational speeds are controlled individually. By targeted control of wheel speeds, linear and rotational motions can be combined arbitrarily. Implementation is based on inverse kinematics models. Omni-wheel drives are used especially in robotics, particularly for compact mobile robots with high manoeuvrability requirements [11, 15, 29].

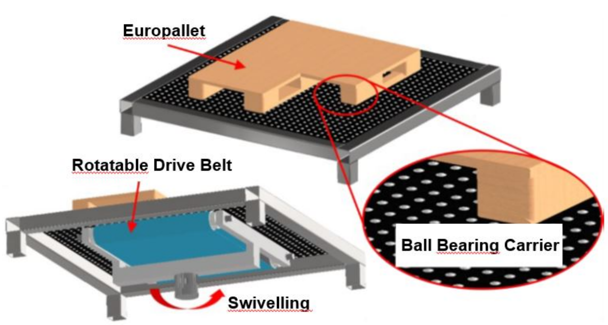

Figure 1: Ball Drive with Rotatable Traction Belt

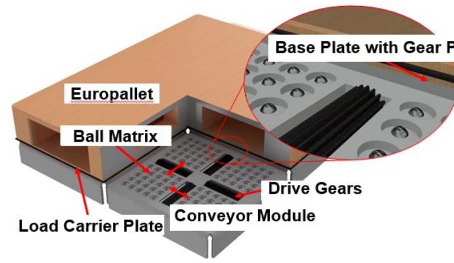

Figure 2: Ball-and-Gear Drive

Mecanum-Wheel Drive
The Mecanum drive uses four special wheels that carry rollers arranged at an angle on their circumference. By targeted variation of direction and speed of the individual wheels, an omni-directional motion can be realised without swivelling the wheels. The resulting motions—forward travel, lateral shift or rotation—arise from the vector sum of the individual motions. This drive concept is known in particular from the field of AGVs and has proven itself there due to its high flexibility and comparatively simple mechanical structure. The Mecanum drive is particularly suitable for applications with limited installation space and high manoeuvrability requirements [30, 31, 29, 12].

Swivelling Roller
This concept is not directly the commonly used “swivelling roller” with internal individual drive, but an arrangement of several driven wheels within a module that are operated together by a single motor. The motor provides both the drive for the wheels and the swivelling motion of the entire wheel unit about a vertical axis. A conceptual design can be seen in Figure 3. By simultaneously swivelling all wheels of a module, the direction of motion of the goods can be adjusted flexibly without having to control individual wheels separately. In combination of several such modules within a surface, linear motions, lateral and diagonal conveying as well as rotation of the goods about their own axis can be realised. The mechanical design largely uses standardised components, keeping technical complexity and costs low compared with fully omni-directional drive systems. Direct pallet conveying is possible, provided that the supporting structure and wheel geometry are adapted to the un-

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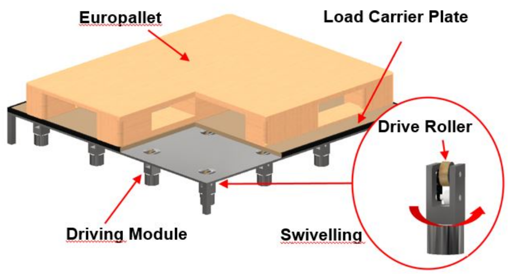

Figure 3: Swivelling Roller

derside of the load carrier. Owing to simple integration and compact design, the concept is particularly suitable for modular surface conveying systems requiring a balanced combination of freedom of movement, economy and robustness[28, 6].

4.2 Evaluation

After the presentation of the drive concepts under consideration, a systematic evaluation is required to assess their suitability for use in the modular heavy-duty pallet conveyor module in a comprehensible manner. Because the solutions presented exhibit different technical approaches, motion principles and integration options, a direct comparison is possible only if uniform, requirement-derived criteria are used. To this end, the previously described requirements — comprising the general functions of intralogistic conveyor systems, the specific requirements of the heavy-duty sector and the focal points identified from the research gap — are consolidated into overarching, combined evaluation criteria. These criteria form the basis for the structured concept comparison.

4.2.1 Directional flexibility

This criterion describes a system's ability to execute motions in different directions and to combine them smoothly. It encompasses linear transports, lateral displacements, turning and alignment operations as well as the realisation of free multidirectional planar motions without additional aggregates. Included is the extent to which mobility supports use in compact, modular warehouse layouts.

4.2.2 Technical complexity

This comprises the constructive, control and integrative effort required for implementation. Assessed are the difficulty of mechanical and electrical integration, the effort for scaling and retrofitting as well as the demands on maintenance. Modular integration into existing infrastructures with high system robustness has a positive effect on this criterion.

4.2.3 Cost

This criterion covers both investment and operating costs over the life cycle. In addition to procurement costs for drives, controls and mechanical components, maintenance effort, spare-parts costs and energy consumption are considered. High energy efficiency and low maintenance costs improve the rating.

4.2.4 Storage availability

Here, the efficiency with which the usable storage area can be occupied under use of the respective system is assessed. Influencing factors are the necessity of an additional load carrier, the possibility of direct pallet movement, integration into walkable and drivable surfaces, and the ability to form or dissolve buffers flexibly without blocking access to other load units.

4.2.5 Weighting of evaluation criteria

The weighting of these criteria is oriented to their importance for use in the modular heavy-duty pallet conveyor module. Priority is given to directional flexibility with a weighting of 0.3, as it directly determines adaptability to complex material flows. Technical complexity and cost are each weighted at 0.25, as they significantly influence technical and economic feasibility — especially regarding use by small and medium-sized enterprises. Storage availability receives a weighting of 0.2 and adds an area-efficiency aspect that influences overall economics.

4.3 Weighted comparison according to VDI 2225

On the basis of these four evaluation criteria, the drive concepts described above are now analysed qualitatively and quantitatively. The aim is to present the strengths and weaknesses of the individual approaches with regard to the requirements of the modular heavy-duty pallet conveyor module transparently. Qualitative evaluation is carried out as an assessment of each criterion's fulfilment per concept; quantitative evaluation is conducted as a weighted utility analysis according to VDI 2225. The specified weightings enable direct comparability of the overall results.

4.3.1 Qualitive comparison

Directional flexibility

The ball-and-gear drive, the ball drive with swivelling belt, and the omni/Mecanum solutions achieve very high directional flexibility in their basic configuration. All four systems enable linear motions in arbitrary directions as well as rotation about the own axis. This allows flexible adaptation to a wide variety of material flows, which is advantageous in compact, modular layouts. The swivelling drive-roller formally does not offer full omni-directionality, but, through targeted control of multiple roller units, can realise bidirectional and flexible diversion motions. In structured installations with defined flow directions, it can thus provide a sufficiently high degree of freedom to implement direction changes efficiently with low mechanical effort.

Technical complexity
Technical complexity varies significantly between the concepts. The ball-and-gear drive requires precise coordination between gears, the ball rollers above and specially formed load carriers, resulting in high constructive effort and integration demands. In the ball drive with swivelling belt, the technical challenge is likewise high, as suitable balls that can be driven from below while being loaded from above are currently not available and would have to be developed. Omni- and Mecanum systems are mechanically less complex but require sophisticated controls with precise coordination of multiple independently driven wheels and continuous vector calculus for motion control. The swivelling drive-roller, by contrast, largely uses standardised assemblies from conveyor technology, is comparatively simple in construction and enables robust integration with low development risk.

Cost
The cost assessment includes both investment and operating costs. The ball-and-gear drive and the ball drive with swivelling belt fall into the upper cost range due to special, non-standardised components and high manufacturing requirements. Heavy-duty variants of omni- and Mecanum drives are particularly cost-intensive; prices per wheel or wheel set in the range of several thousand euros are common depending on manufacturer and load range. For heavy-duty variants with capacities above 800 kg per wheel, acquisition prices of €3,000–5,000 per wheel are not uncommon. Considering the required number of wheels per square metre of conveying surface, material costs for the drive wheels alone can quickly add up to over €50,000 per square metre. To ensure economic viability, a target value of approximately €40,000 per m² is envisaged for the planned system.

Storage availability
Storage availability depends significantly on whether an additional auxiliary carrier — e.g., a special load carrier — is required. In the ball-and-gear drive, omni and Mecanum concepts, such a carrier is necessary to reliably realise the motion function. This can restrict occupancy density, as ejections are often possible only when adjacent positions remain free — costing area efficiency in highly condensed storage systems. The ball drive with belt and the swivelling drive-roller can in principle move pallets directly, without an additional carrier. This opens up the possibility of denser occupancy and more flexible buffering, provided that the constructive and surface-technical boundary conditions of the pallet are respected.

4.3.2 QUANTITATIVE COMPARISON

To conclude the assessment of the presented drive concepts, a utility analysis in accordance with VDI 2225 is carried out. The objective is to compare the suitability of the different technical approaches with respect to the previously defined and weighted criteria — Directional flexibility (0.30), Technical complexity (0.25), Cost (0.25), and Storage availability (0.20) — in an objective manner. VDI 2225 provides a standardised procedure by which technical and economic requirements are transformed into a comparable, quantitative form.

The evaluation is performed on a scale from 1 (very poor) to 5 (very good) for each criterion, with the respective weighting entering the calculation of the overall utility value. For unambiguous interpretation, high technical complexity as well as high cost are rated with lower scores, so that a high score in all criteria indicates a positive aspect of the respective concept. The qualitative judgement is based on the analysis of the design principles, the integration effort, the economic feasibility, and the effects on the usable storage area. The calculated utility values provide the basis for a transparent ranking of the concepts. Table 2 shows the assessment of the five concepts in the order of their presentation, including the resulting utility values.

The evaluation shows that the swivelling drive roller achieves the highest ranking with a utility value of 3.5. The decisive factors here are its comparatively low technical complexity (rating 4) and the associated low costs (4), combined with good stock availability (3). Its directional flexibility (3) is lower than that of fully omnidirectional systems, but is sufficient for many applications.

The ball drive with drive belt ranks second with a score of 3.0. Its strengths lie in its very high directional flexibility (4) and good stock availability (4). However, the rating is limited by the high technical complexity (2), due to the necessary redevelopment of suitable ball components, as well as moderate cost values (2).

Omni wheels and Mecanum wheels each achieve a utility value of 2.65. Both concepts offer the highest directional flexibility (5). However, these concepts fall short due to their high technical complexity (2), resulting from complex control systems, very high costs (1) and low stock availability (2). The latter is due to the fact that the wheels are made of plastic and would be damaged without an additional load carrier. The necessary use of such a carrier reduces the occupancy density and thus the availability of storage space.

The ball and gear drive comes in last with a utility value of 2.6. Although it achieves good directional flexibility (4), but their high technical complexity (2), moderate costs (2) and low storage availability (2) lead to an overall weak rating.

Resulting from this evaluation one possible approach to the design of the transport module is shown in Figure 4. This presents a first rough idea of the final design but it is already apparent that a pallet transport is unlikely like this as the distance between two center points of each roller is 20 cm. Given the dimensions of a Euro-pallet there would

Concept	Directional Flexibility	Technical Complexity	Cost	Storage Availability	Utility Value
Weights	0.3	0.25	0.25	0.2	
Ball-and-gear	4	2	2	2	2.60
Ball + belt	4	2	2	4	3.00
Omni-wheel	4	2	1	2	2.65
Mecanum-wheel	5	2	1	2	2.65
Swivelling roller	3	4	4	3	3.50

Table 2: Comparison of different concepts

not be continues contact with all racks and the rollers. But it seems likely that by changing the layout of the module a continues contact can be achieved and henceforth a direct transport without intermediate carriers might be possible. An investigation into this possibility will be conducted in a following paper. Finally, the vision of the autonomous modular transport system can be seen in Figure 5.

5 Conceptual design of the control system

As this research aims specifically for a setting where humans are expected to be able to move freely while the modules perform their tasks simultaneously, the challenges for a control concept are numerous. Not only is an efficient planning and movement algorithm essential for economic success but there is also a significant need to guarantee safety for not only the goods but more so for the workers within the warehouse. In this section concrete requirements are derived for the overall system and the control algorithm and present the control concept that satisfies all requirements as well as the hierarchical structure.

5.1 Preliminary requirements

5.1.1 Safety

One of the main aspects to consider in the development of new machinery is its safe performance and the safety of the personnel working with or beside it. For the transport system the only safety threatening situation can arise when a pallet crosses paths with either another pallet or a worker (with or without load). To guarantee safety the aim is to prevent reaching such situations. To do so a measurement system is required that can detect all objects and workers. An easy solution is the usage of cameras throughout the warehouse. By mounting them at different locations in an upper part of the warehouse and/or the ceiling an area-wide surveillance can be implemented and through object detection not only can humans be detected but also every pallet. By doing so, positions can be calculated and tracked which furthermore can be used to keep pallets and humans away from dangerous situations. The exact method on how this is done will be explained in 5.2.3.

5.1.2 Flexibility and scalability

As warehouses come in different shapes and sizes the modules' algorithms must be able to dynamically fit into each setting and keep up with environmental changes. Thus, a

Figure 4: First idea for a module consisting of an arrangement of rollers

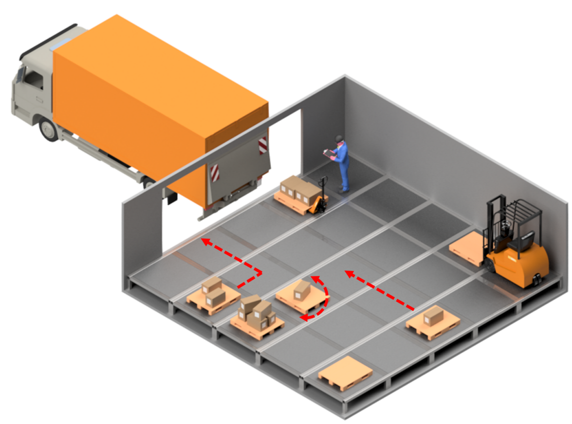

Figure 5: Vision of the autonomous modular floor

degree of flexibility must be achieved without compromising on its computational time with increasing layout sizes or pallets. Flexibility also takes the ability into account to work without problems even if a module fails and becomes out of order. This is crucial as otherwise all other modules would need to be shut down, too, until the problem is resolved. Hence, the algorithm must automatically identify the failed module and work around it until it is repaired, in which case a flawless reintegration into the system must take place.

5.1.3 Multidirection

In the current state of this research it is still an open question if an omnidircetional transport is desired. This will mainly depend on the results of the investigation into the ability of moving pallets without additional intermediate carriers. Up until that point a bidirectional transport is assumed with the possibility of expanding the algorithm.

5.1.4 Human-machine-interaction psychology

To achieve a feasible application in practical settings one of the main aspects to consider is the safety of human workers that will work alongside the modules. Robots are nothing new in industrial fields, but settings in which autonomously acting machines are able to (potentially) interact with humans is still not the norm. Therefore, there still exist skepticism and doubt within those that work in human-machine-interacting environments, probably even more so when there is no prior experience of the worker with such machines. In [32] several papers are reviewed that investigated the safety perception of humans who were required to work with robots. It yields insights into what makes workers feel safe when interacting with robots. Among numerous aspects that affect safety perception (like the appearance of the robots or the noises made by them) one key factor is the navigation behavior. According to the paper, a robot that displays courtesy cues (e.g. stopping and retreating) leads to 'significantly fewer hesitation events', which in turn results in a more fluent workflow. This will come back at the presentation of the movement algorithm itself. It must be said, however, that the investigated robots in the paper were AGVs and AMRs and therefore do not quiet represent the modules. As a result the paper might not apply this case. Nonetheless, it is still estimated that the navigation part of the paper as helpful insight for the design of the movement algorithm.

5.2 Movement algorithm

5.2.1 Centralized vs. decentralized structure

When it comes to the way a system operates (especially in multi-agent path planning), there are essentially two modi operandi: centralized or decentralized. In the former setting all available information are gathered into a main server which then processes them to calculate appropriate actions for the next time step and directs instructions to each element of the whole system to carry out. This approach yields a very clear and easy system structure with easy access to all information. In contrast, the decentralized approach lets each element of a system calculate their own actions by processing only locally available information. A comparison between these two approaches in the context of swarm coordination is presented in [33]. Since this research's setting is in essence a swarm coordination problem the results of the paper can be directly applied to this research. In it, the centralized strategy yields better decision quality while the decentralized one scales much better with the number of agents within the swarm. Since an initial simple movement algorithm with an unknown amount of agents is desired a decentralized approach seems like the better option for this research.
As the warehouse service problem (aka WSP) needs to be addressed to guarantee smooth operating warehouses we need a structured approach to be successful. Taken from [34] and modified to this case, within the problem four questions must be answered:

1. Where should goods be stored? (Organization)
2. Which task should an agent perform? (Task allocation)
3. When must a pallet be at a given position? (Scheduling)
4. How does it reach that position? (Path planning and execution)

These considerations can be dealt with by following the example of [35] and split the tasks within the overall system. The tasks will be divided into four different categories: external, organization, system and module, whereas the external and organization parts are centralized elements outside the modules while system and module are local elements. External handles every information that lie outside the systems measurements, like dates of incoming transporters. In the organization block the warehouse organization is processed and maintained. This includes the allocation of pallets to a position in the warehouse (by a predefined algorithm which will be the subject of a future paper) and the handling and processing of all surveillance camera pictures. From this, the system block evaluates obstacles from the processed camera pictures and calculates the next movement step. Lastly, the module receives the movement instructions and executes them, i.e. move the pallet into the desired direction. Additionally, it reserves the desired next module, which will be elaborated on in the movement algorithm section.

5.2.2 Collision prevention

Since these modules are supposed to be implemented into an existing warehouse filled with people the biggest chal-

lenge is to avoid collisions. This is especially difficult since a parallel transport system that enables a fully accessible floor without blocked or dedicated areas is aimed for. Furthermore, humans are mostly considered unpredictable, especially when the robots decisions/moves can influence a humans actions. This is often times neglected in papers of this nature but a significant part in real applications as is shown in [32]. The reason why courtesy cues lead to a more fluent workflow is most likely because humans learn that robots retreat from them, making them more predictable and therefore gives humans more confidence in their own decisions. As [36] point out, standard strategies cannot reliably deal with such obstacles. Take for example Artificial Potential Fields (APF) and Model Predictive control (MPC) which inherently include obstacle avoidance with smooth trajectories. While APF can struggle with moving obstacles and might end in deadlocks, MPC struggles to reliably find feasible paths to its goal. In both cases the behavior of human obstacles cannot be predicted (reliably) resulting in new problems. Since human avoidance is an active field of research there are already existing schemes that complete the task successfully but they either scale very badly and/or have not been tested in practical applications (e.g. [36, 37]) or are simply too complex for this setting (e.g. [38, 39]). Furthermore, schemes that consider only bidirectional movements could not be found at all.
A potential method for obstacles avoidance with bidirectional movement and unpredictable obstacles is to implement a traffic like rule set. However, this would require to teach those rules to the workers and demand full focus at all times and abiding by those rules. As in normal traffic this is not feasible, especially since forklifts (that are carrying loads) can hide objects in its path. Although there are methods to solve this problem, for example with augmented reality approaches like [40] presents, but this would require to upgrade forklifts and equipment, leaving this solution as cost intensive and as a result undesirable. Therefore, inspired by [32] and [36], a simple ”wait and retreat”-strategy is applied. This can easily be done by implementing a prioritization system to the movement algorithm. Not only does this prevent collision with humans but also with other pallets. The next section will explain in detail how this is applied.

5.2.3 ALGORITHM

To start off the question of how to reach the goal position of a pallet can be guaranteed. The most straight forward approach is to move (directly) towards it. This can be done by taking the distance between the current position and the goal to then reduce it at each iteration. This is called a greedy algorithm as it only takes an optimal local solution of a decision process without considering the global context (for a more detailed explanation check out for example [41]). Among this group of path planning algorithms the most prominent ones are the A* and Dijkstra algorithms which are still refined and improved on (e.g. [42, 43]). In contrast to the classical approach of those algorithms the one presented here does not search for a full length path towards the goal but only for the next step as a big draw back of the two is the bad scalability with the amount of obstacles and environment size. So, to calculate which of the four adjacent positions the pallet should move to next the algorithm decreases the Manhattan/taxicab distance and moves in either x- or y-direction towards the goal. This is a commonly used heuristic in path planning (for example in A* algorithms) as it guarantees to reach the goal directly. The only requirement for this to work in practice is to have information of the current position and the goal of the pallet, which can easily be tracked. Another advantage is the low complexity of the algorithm itself but as it does not take other information into account collisions are very likely.
To tackle this problem the aforementioned ”wait and retreat”-strategy is implement by prioritizing each pallet as well as workers and forklifts. First, a module calculates the next position of the pallet on top of it, then it checks if that desired module is already occupied by sending a request to it. If the module is free the pallet gets moved there, if it is occupied by another pallet it checks for its priority and either waits or asks the desired module to move that pallet. A more detailed explanation about what happens then follows shortly. If a person or vehicle is detected by the surveilling camera system the module calculates the relative position and moves the pallet away from the object in the opposite direction. This is also an easy task for the module and it should decrease workflow problems as mentioned in the previous section.
Now only one problem is left and that is what happens if a module is already occupied by a pallet when another module wants its current pallet to move there? Here again the priority system is used: if the blocking pallet's priority is higher nothing happens in this iteration as it implies that the blocking pallet will move in the next iteration, if it is lower that module is asked to move the pallet out of the way. But what if the pallet cannot be moved because all adjacent modules are also occupied with pallets? In this case that module sends requests to all those blocking modules and asks them to move. This process repeats until a movable pallet is found can be considered a tree search whereas upon finding a valid move the tree provides a sequence of actions by backtracking the tree's order to free up the desired space. With this approach the final problem of resolving clustered pallets is solved and the movement algorithm is completed. In case the two competing pallets contain the same priority a ”first come first serve” philosophy is applied.
Finally, the priority system can be used further to define broken modules. This way broken modules can be excluded from the algorithm automatically and easily be reimplemented. To still be able to find a way around such modules, even if the Manhattan distance can only be decreased by going in a straight line through that disabled module, by simply forcing the palette to move perpendicular to its original direction the situation can be resolved. In

a worst-case scenario where multiple modules fail and create one or more dead-end modules, they will be flagged as broken within the algorithm as well but not for the maintenance team. A pseudocode of this algorithm can be seen in Algorithm 1.

In a following paper, a thorough simulative investigation of this algorithm will be performed and additionally the organizational planning within the warehouse to optimize productivity will be a focus point.

6 CONCLUSION

In this contribution, the state of the art of conveyor types for unit-load and heavy-duty transport was systematically analyzed and evaluated with respect to multidirectional surface conveying. A research gap was identified: the absence of a modular, surface-capable heavy-duty conveying system that provides continuous, multidirectional motion at high availability while explicitly addressing pallet transport as a widespread, standardized load carrier. On this basis, load assumptions for pallet/heavy-duty operation and requirements for scalability and modularity were derived. Several drive concepts were designed and evaluated using a VDI 2225 utility analysis. The swivelling roller concept achieved the highest overall utility due to low technical complexity and cost, combined with sufficient freedom of motion and favorable area efficiency.

In addition, a decentralized movement algorithm was developed from the application requirements. Computation is performed locally on each module, which determines the next position of the pallet currently transported, rather than relying on centralized trajectory planning. Communication is minimized by restricting interaction to status queries to the next desired module, thereby reducing bandwidth usage and coupling between components. This design results in low computation latency, scalability with floor size and pallet volume, and flexibility with respect to layout concepts and changes. Operational safety is addressed by integrating vision-based surveillance to detect hazardous situations for goods and workers and to prevent collisions. Fault tolerance is supported by status-based exclusion and seamless reintegration of defective modules. A priority scheme resolves routing conflicts, creates protective margins around humans, and suppresses oscillatory back-and-forth behavior of pallets at intersections. The algorithm is heuristic rather than optimal; however, it satisfies the current set of requirements and provides a scalable, modular and safe basis for the proposed system with the chance of extension if so desired.

Future work comprises a methodical substantiation of the choice between direct pallet conveying and the use of an intermediate load carrier. Physics-based simulations of alternative roller layouts (e.g., stagger, zoned actuation) will be conducted to optimize the contact area such that a minimal number of simultaneously driven rollers ensures adequate force transmission into the pallet structure. The modelling will incorporate contact and friction conditions, permissible surface pressures, and geometric tolerances. On the basis of these results, the constructive elaboration of a module/prototype will follow (mechanical structure, sizing of drives and bearings, coverings, interfaces, control and safety aspects), accompanied by experimental validation under application-oriented conditions including movement performance, transfers, energy demand, availability, and wear, together with a systematic comparison of direct conveying versus intermediate load carrier. Methodological extensions for the decentralized algorithm — such as formal verification of safety and deadlock-free priority scheduling, and analysis of warehouse organization optimization.

Algorithm 1. Movement Algorithm

```
Choose movement direction from Manhattan Distance
Check if adjacent module in corresponding direction is available
if Desired module is out of order then
    Set perpendicular modules as desired modules
end if
if Desired module is available then
    Move palette
else if Desired module is blocked by human then
    Retreat
else if Desired module is blocked by palette then
    Initiate search tree, starting with desired module
    while No empty space found do
        Add adjacent modules to search tree
        Check adjacent modules
        if Empty space found then
            Execute moves to free up space
            return
        else
            Go to next branch of the search tree
        end if
    end while
end if
```

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