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AUTONOMOUS SHUTTLE SYSTEMS − REQUIREMENTS, FUNCTIONALITY AND DESIGN CONCEPTS

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Abstract: *With the advent of cellular transportation systems, intralogistics met a completely new concept of materials handling. The advantage of this technique is its ability to provide increased productivity and flexibility of material flow combined with a high degree of automation. Despite many advantages, the industry has hardly adopted the concept, due to high cost and the effort that is necessary to develop the hardware. Implementing modular assembly kits can help reduce the workload. In addition, modular assembly kits allow for a simple exchangeability of components based on individual requisitions. The purpose of this paper is to present a new modular design catalog and knowledge representation for autonomous shuttle vehicles, providing an integral approach with the advantage of both open path navigation on the shop floor as well as inside an automated storage system. Current systems are analyzed according to their tasks and functions. With the results of the analysis, requirements of possible new systems are defined. Based on a requirements list, four essential subassembly modules are categorized: carriage and drive train, sensor technology and control, energy management and load handling devices. In a knowledge-based engineering approach the interrelationships and dependencies between each module are demonstrated. The combination of technical solutions contained in the design catalog allows the creation of several potential systems. A total of three exemplary shuttles are described from different perspectives: the shuttle "flexible" is able to handle multiple loads with varying dimensions, the shuttle "standard" describes a single load system similar to vehicles currently used and finally the shuttle "budget" that provides similar functionality at a lower cost.*

Key words: *shuttle system, autonomous guided vehicle, cellular transport system, function-oriented modularization, assembly kit, modular design catalog.*

1. INTRODUCTION

As the markets got more and more volatile over the last years, logistics service provider had the increasing need to deal with changing performance requirements on intralogistical material flow systems. Since conventional conveyor techniques and automated storage and retrieval systems as well as the methods used to plan such material flow systems cannot fulfill these challenges, cellular transport systems were developed. The basic concept of cellular transport systems is to replace conventional conveyors with a decentralized material flow system by distributing the necessary functions to a swarm of small self-organized functional units. This enables a high degree of automation but still provides the flexibility to change the system according to the operator's current needs [1, 2].

Despite the many advantages of cellular transport systems the industry has hardly adopted the concept. The authors are convinced that this is not due to a deficiency of the concept but rather caused by high cost and effort necessary for hardware development.

It is evident that there is a demand for flexible and changeable system architecture, because the latest generation of material handling systems aims to fulfill such requirements. However current systems that incorporate the concept are often a combination of several individual systems that have been developed for other specific tasks. For example the storage process is handled by shelf operating shuttles, while the transportation of the goods to other areas of the warehouse (e.g. work stations) is accomplished using autonomous guided vehicles. A saving in time and money can be expected simply by avoiding the internal transshipment between the individual entities.

1.2. Current research activities

Up to date research has mainly focused on the description of the new concept and the corresponding development of algorithms that enable swarm intelligence or sensor fusion for example [3]. Further schemes like the calculation of the intralogistical performance availability were derived [4].

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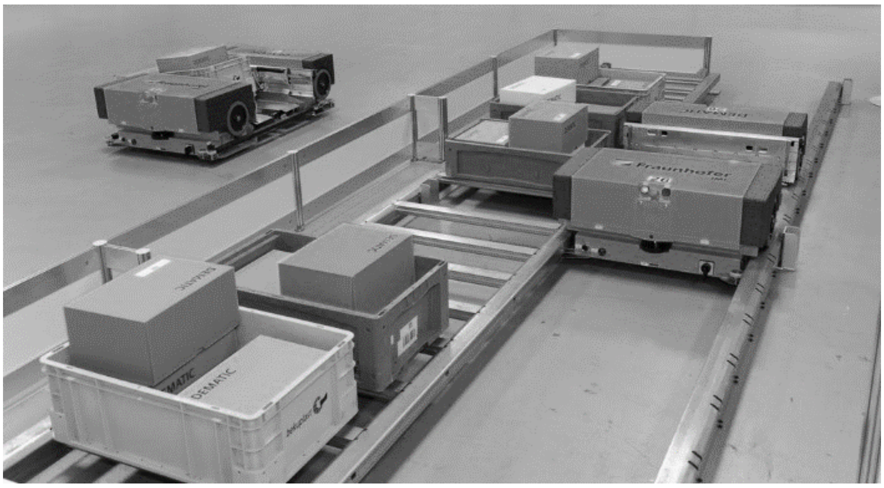


Fig. 1. Fraunhofer Multi Shuttle [source: Dematic GmbH].

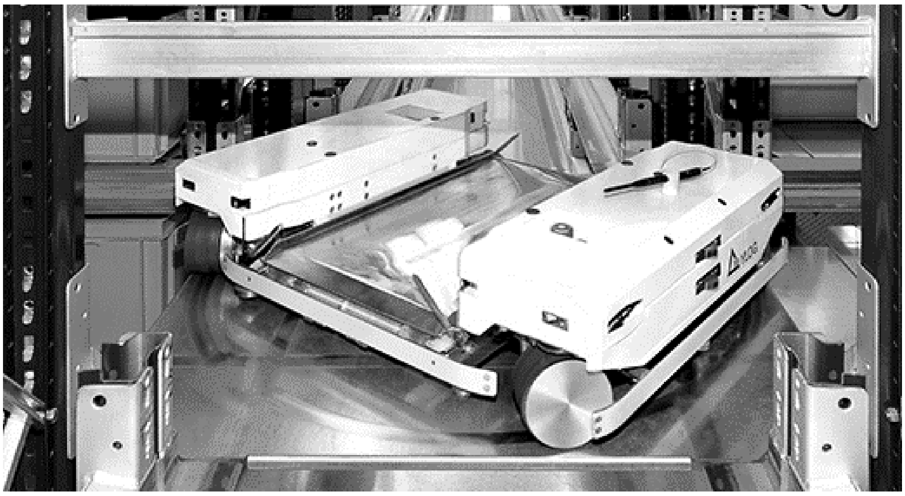


Fig. 2. Ylog AiV [source: Knapp Industry Solutions GmbH].

In the following section current systems are analyzed on a structural level with a focus on hardware development. There are several systems that try to replace conventional conveyor technique but only two qualify as real application of cellular transport systems.

1.3. The Fraunhofer Multishuttle Move

The Multishuttle Move was developed in a close cooperation by the Fraunhofer Institute for Material Flow and Logistics and the company Dematic GmbH. It was the very first prototype that was build based on the idea of decentralized acting entities (Fig. 1).

The vehicles are very similar to the first generation Dematic shuttle vehicles. For example they share the same chassis. While located inside a racking system the vehicle is rail-guided and hence can only move up and down the aisle. In order to operate like an automated guided vehicle an additional drive train and several smart sensors were added. Each vehicle weighs 134 kg and can carry a payload of 40 kg [1, 2, 5, 6].

1.4. Ylog AiV (Ylog-Shuttle)

The autonomous intelligent vehicle (AiV) was initially developed by the company YLOG GmbH that is now a subsidiary of Knapp AG (Fig. 2). The shuttle is also rail-guided but its unique selling proposition is an all-wheel steering. Beside normal operations this special steering concept enables driving at right angles inside the racking system. Furthermore, the system is equipped with lifting devices that can carry the whole shuttle vehicle. This allows the AiV to reach any storage compartment in the racking system.

In contrast to the Multishuttle Move, the AiV is not equipped with the same extent of sensors. Transportation based on open path navigation is not possible hence a rail-based infrastructure is necessary outside a racking system.

The AiV can handle small load carriers with a payload of up to 50 kg [7].

1.5. Aims and goals of the research

The main purpose of this paper is to present a new modular design catalog and knowledge representation for autonomous shuttle vehicles. An integral approach based on specified functions, related requirements and design modules is investigated. The advantage of open path navigation on the shop floor as well as inside an automated storage system is considered.

2. MATERIALS AND METHODS

The VDI-2206 [8] V-model as macrocycle is chosen as basic approach for the elaboration of the design catalog. Further details of the system are derived using the general guidelines VDI-2221 [9] and VDI-2222 [10] for product development and construction methodology.

2.1. Definition of system boundaries and functions

The goal of consolidating autonomous transport vehicles and shuttle vehicles in an integral design concept can be reached by modifying the current system boundaries by either 1) adding the racking system to AGVs or 2) by adding the warehouses shop floor to conventional shuttle systems. The second approach is presented. Intralogistical processes of warehouses demand a highly sophisticated system design. Consequently, in the first step the complexity needs to be reduced by introducing a hierarchical structure, as proposed by general systems theory. Every process that is identified as being essential for the material flow system is specified and structured. As a result the key functions can be defined as main parameters.

In accordance with VDI-2411 [11] and VDI-2860 [12], the following functions are vital for autonomous shuttle systems:

- convey/transport material;
- handle material: change (sort, divide, merge), secure;
- store material.

Figure 3 depicts the essential functions that are linked with the necessary flows of energy, material and information of the intralogistical processes to a functional structure.

2.2. Requirements of the system and its components

In order to develop a method to design a modular material flow system the modularization strategy has to be defined [13]. The process of modularization that is function-oriented is based on the ideas presented in [14] and [15]. Figure 4 illustrates this function-oriented modularization for autonomous shuttle systems. Starting with the highest degree of abstraction the global system requirements are defined by the strategic targets and tasks of the individual warehouse. The sub-elements of the autonomous shuttle system in the first layer of the graphic represent the functions resulting from the global requirements. With increasing concretization within an iterative micro cycle of the V-model, the local requirements for each sub-system can be derived from the global system requirements. Each sub-system consists of technical modules. The main-functions are divided into sub-functions and assigned to the technical modules. Every technical module consists of further sub-modules. These sub-modules represent the most detailed level and hence are very concrete. The degree of abstraction is lowered continuously until all requirements are characterized.

Table 1 shows an example of global requirements of the system as well as local requirements for technical sub-modules. The group wise clustering similar to ordinary assembly groups that is shown in Fig. 4 is a result of the hierarchical structure and can be used to define real assembly groups on the fly. This is useful in order to find solution principles that are likely to fulfill the individual tasks.

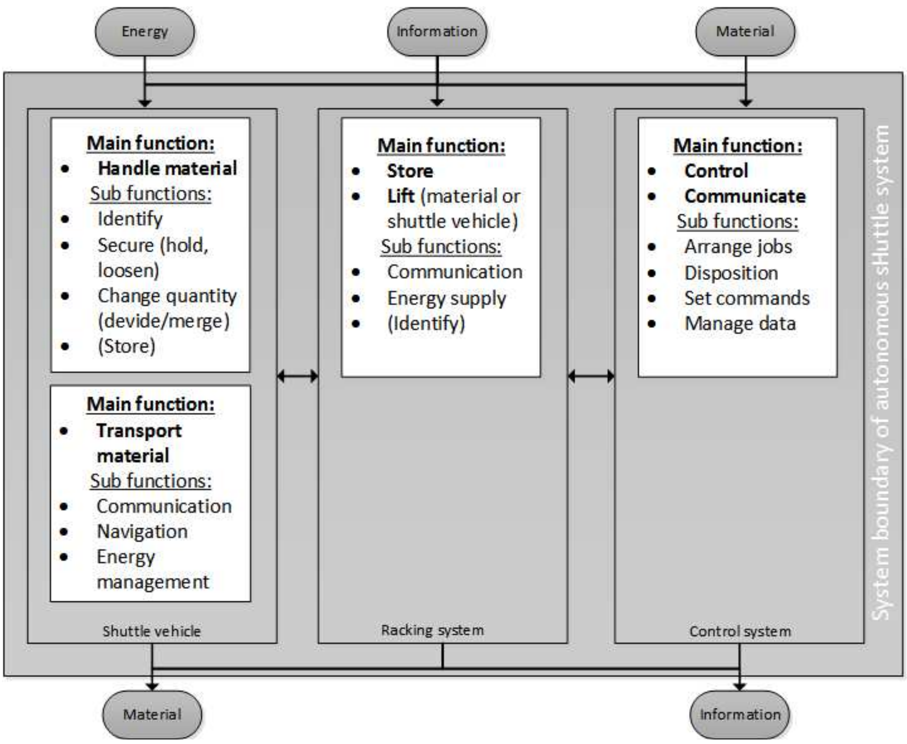


Fig. 3. Functional structure of autonomous shuttle systems.

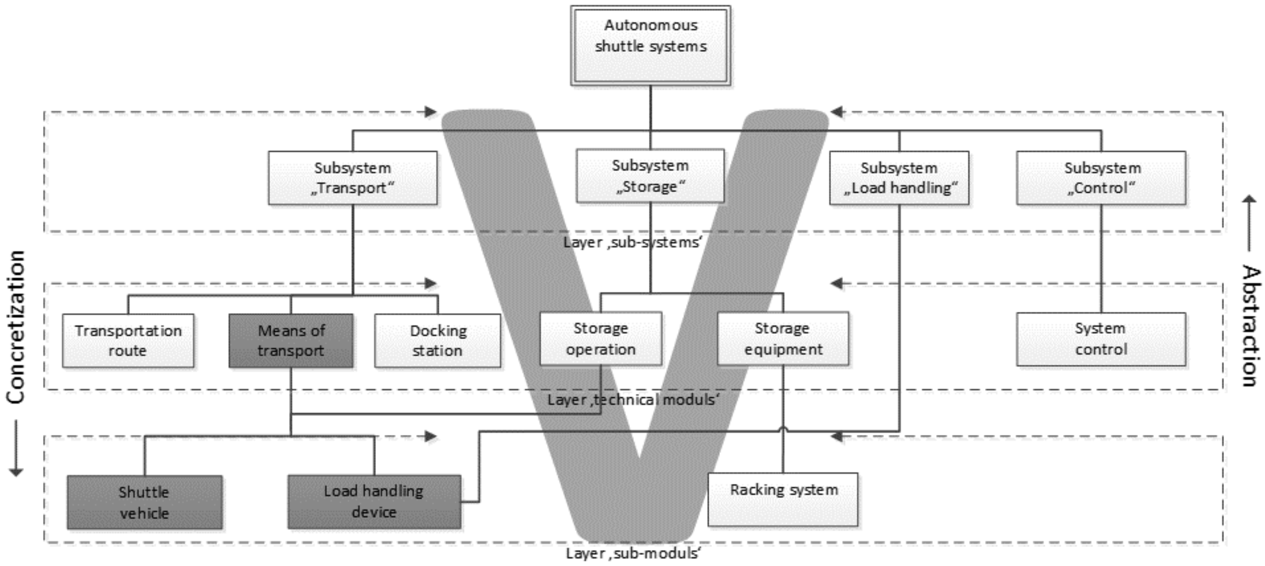


Fig. 4. Function-oriented modularization of autonomous shuttle systems by using the V-model**.**

Table 1

Excerpt of the requirements list

Organizational and process data		Description of requirements	Value
Type	Phase		Unit
		System	
		General basic conditions	–
		Throughput	[TU/h]
		Availability	[%]
		Storage capacity	–
		Nominal power consumption	[kW]
		…	
		Load carrier	
		Type	–
		Dimensions	[mm]
		Mass	[kg]
		Payload	[kg]
		Specific properties	–
		…	
		Shuttle vehicle	
		Dimensions	[mm]
		Total mass	[kg]
		Total payload	[kg]
		Freedom of movement	–
		Max. speed	[m/s]
		Max. acceleration	[m/s²]
		Nominal power	[W]
		…	

Following the guideline VDI-2510 [16] the following subassemblies can be identified for autonomous shuttle vehicles:

- undercarriage: travelling-gear concept, suspension, drive train, steering, brakes;
- load handling device;
- warning and safety devices;
- vehicle control system;
- energy supply and management;
- operating elements;
- devices for position determination and localization;
- data transmission.

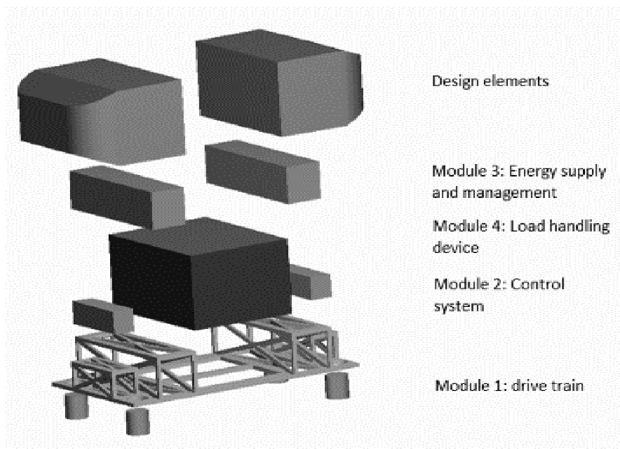


Fig. 5. Modular design of an autonomous shuttle vehicle.

Since modularization is a prerequisite of the design catalog, the subassemblies are grouped into a feasible assembly kit that can easily be changed and adapted. This further enhances the flexibility. The structure is shown in Fig. 5. Finally, some subassemblies are consolidated into one module.

3. RESULTS

3.1. Modular design catalog

On the basis of well-known solution principles from autonomous transport vehicles and conventional shuttle vehicles a complete design catalog is compiled. The purpose of a design catalog is to assist in a systematic engineering process with structure and accessibility to knowledge. The format described in [17] is used for the one-dimensional design catalog.

The knowledge that is contained inside is based on literature and guidelines like VDI-2510, the authors experience and industry-accepted technologies.

Additionally all determining parameters and interfaces for each subassembly are listed. The quality of the parameters and the values respectively are assessed based on the information's certainty and are marked in colors.

3.2. Knowledge representation

To demonstrate the interrelationships between the modules of the assembly kit a design structure matrix is used. Classes of interrelationships are defined as physical, mechanical, electrical and informational relations.

Fig. 6 depicts the complete design matrix showing all four types of relations and clusters that are automatically determined by the program.

Physical interrelationships represent all direct connections that transfer forces except for mechanical power which is represented by the mechanical ones. Electrical interrelationships primarily represent the transmission of electrical power and have to be subdivided into permanent and regulated energy supply according to the electrical components. All informational interrelationships represent direct or indirect connections (bus-system) that are used to exchange information and data.

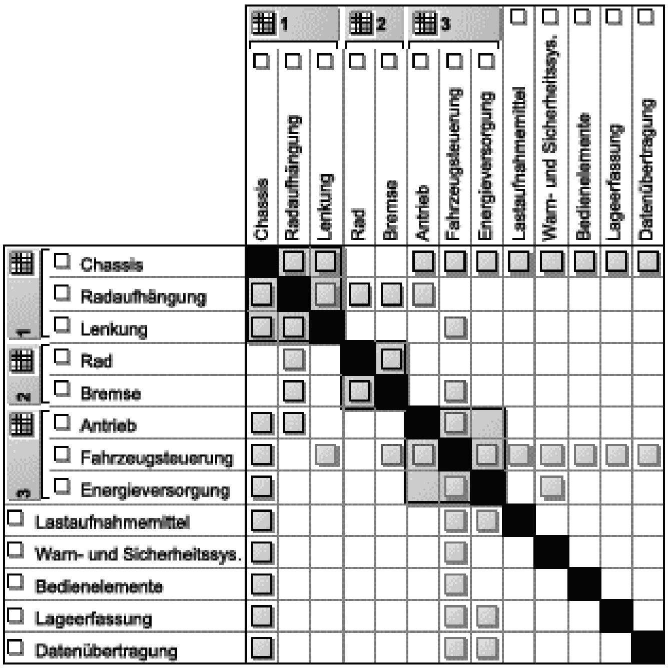
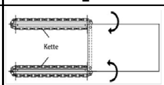
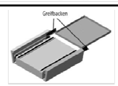
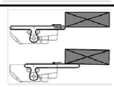
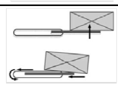
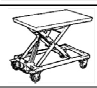
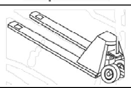
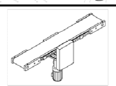
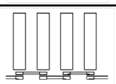


Fig. 6. Design structure matrix.

Table 2

Excerpt of the modular design catalog showing different types of load handling devices

Classification part			Principal part			Access part				
Type of handling	Basic principle	Implementation	Common name	Generic picture		Multi-deep storage	Type of load carrier	Velocity	max. payload	Package space
1	2	3	1	2	Nr.	1	2	3	4	5
Carry over	Pull	Chain	**Chain conveyor**		1	no	tray	0,6 m/s	250 kg	10
	Grasp, clamp	Guide rail	**Clamps**		2	yes	bin/tray	1,2 m/s	100/250 kg	9
Underride	Telescope	Belt	**Telescopic belt**		3	yes	bin/carton	0,8 m/s	50	4
		Table	**Telescopic table**		4	~	bin	0,4 m/s	50	7
	Rigid plattform		**Lifting table**		5	no	all	-	500 kg	3
		Fork	**Fork**		6	yes	palett	-	1.000 kg	7
Pass over	Convey	Belt	**Belt conveyor**		7	no	all	0,5 m/s	1.000 kg	6
		Roller	**Roller conveyor**		8	no	all	0,5 m/s	1.000 kg	6

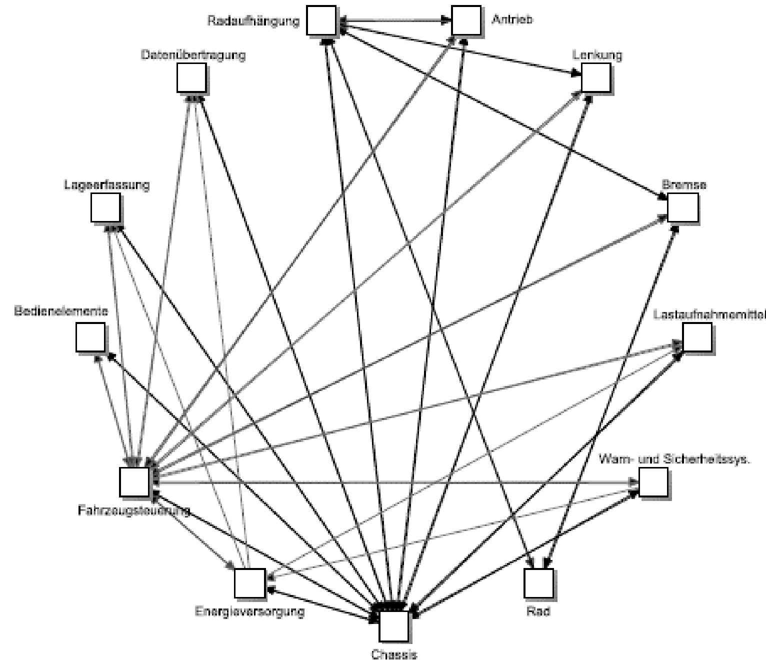


Fig. 7. Graph showing uni- and bidirectional dependencies between the subassemblies.

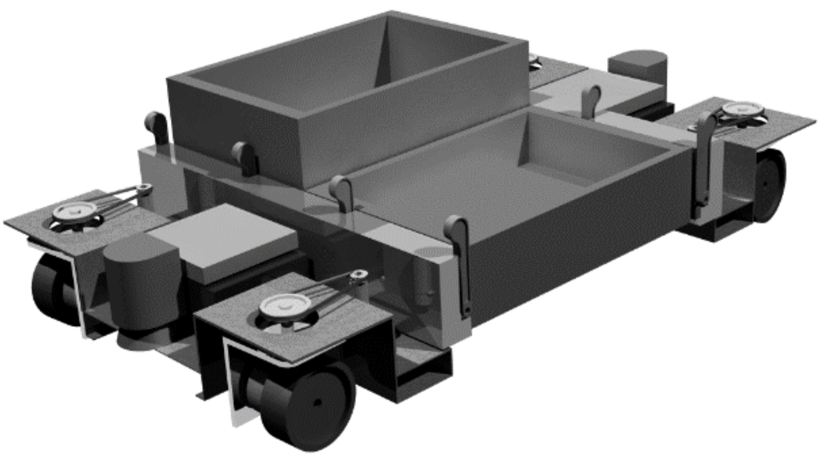


Fig. 8. Rendering of the shuttle ‘flexible’ carrying two loads.

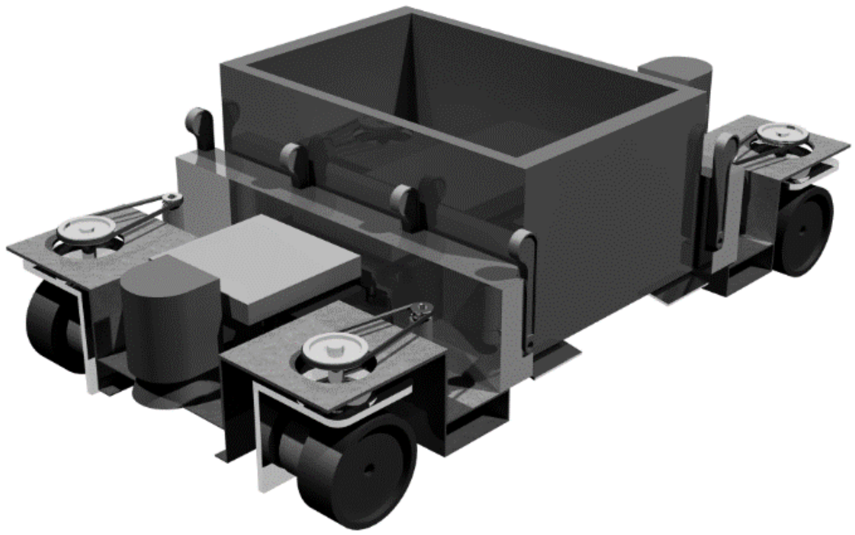


Fig. 9. Rendering of the shuttle standard.

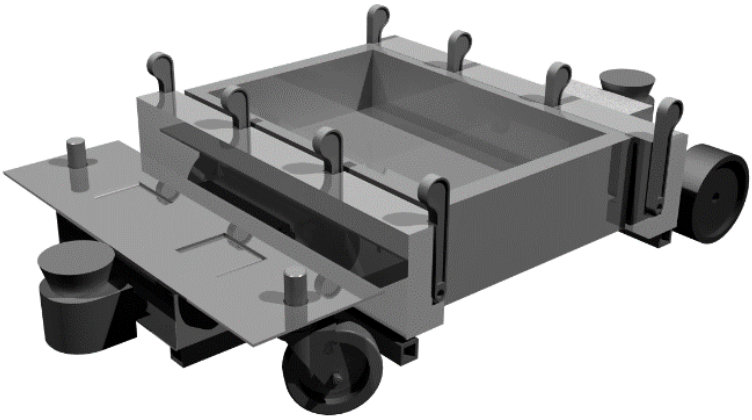


Fig. 10. Rendering of the shuttle type budget.

Another possibility to illustrate the dependencies between the subassemblies is depicted in Fig. 7. The arrows in the graph linking the elements can be either uni- or bidirectional resembling the reciprocal influences.

Finally the knowledge can be concentrated using an ontology editor. The ontology can be browsed using queries. This allows the illustration of:

- the modular structure;
- exemplary instances of the assembly kit;
- the main determining parameters;
- the degree of requirements fulfillment based on the requirements list;
- reciprocating influences between the modules;
- the interrelationships according to the design structure matrix.

3.3. Design concepts on a modular basis

The simplicity of the modular design catalog and smart visualization of the knowledge representation can be used to develop the pertinent modules of the assembly kit and to form an autonomous shuttle vehicle without hassle. A total of three exemplary shuttles are described from different perspectives to demonstrate the capabilities of the elaborated engineering concept.

The first prototype is called "flexible", as it is the most v ersatile draft. It is designed to handle multiple loads with varying dimensions ranging from 200–800 mm. This is achieved by using a load handling device that is adjustable in length. Furthermore the load handling device is capable of storing goods double deep in the shelves of the racking system to increase storage density. The chassis is conceived as torsion-resistant sheet metal construction. The drivetrain is configured as all-wheel drive and all-wheel steering, providing the highest degree in freedom of motion. A lithium based battery system in conjunction with capacitors, provides power to keep the vehicle up and running during a normal work shift. Figure 8 shows a rendering of the shuttle.

The second shuttle (Fig. 9) is called "standard", as it describes a vehicle with conventional but industry-proven technology. It is designed to carry a single load with static dimensions of 400 × 600 mm. The chassis, drivetrain and steering are identical to the first solution.

The third shuttle (Fig. 10) is called "budget" as it provides similar functionality at lower cost. The focus is set on practical solutions. This comes with compromises, e.g. in terms of freedom of motion. The drivetrain is able to provide open path navigation, but only with two degrees of motion because the steering is designed as a differential drive. The energy supply is based on cost-efficient NiMH accumulator. It is able to carry a conventional small load carrier.

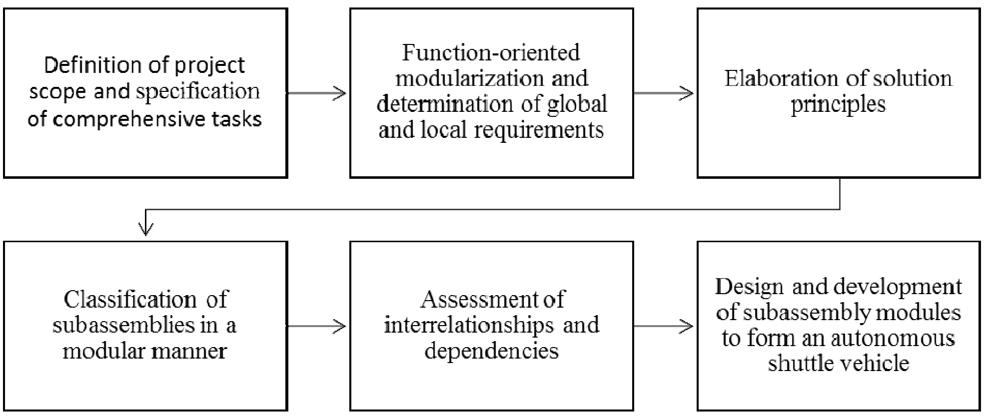


Fig. 11. Overview of design concept.

4. CONCLUSION

An innovative design concept (see also Fig. 11) using a modular design catalog has been introduced. It assists engineers in defining the products capability and functionality using proven guidelines. A function-oriented modularization helps deriving system requirements on different levels of abstraction leading to concrete components of autonomous shuttle vehicles. Different solution principles can be elaborated using literature or creativity techniques.

The subassemblies can be further classified in a modular manner to form adjustable assembly kits. The knowledge representation of ontologies and design structure matrices can be used to assess the reciprocating interrelationships of the subassemblies and their parameters. Different solution principles can be applied to fit individual requisitions. Finally a detailed determination of these parameters can be realized that leads to the final configuration of the subassemblies and the assembly kit.

Three examples with different scope illustrate the potentials of the outlined process of engineering and product development.

5. OUTLOOK

A first draft to enable a rough automatic computation of parameters like driving power or operating range for an initial specification is implemented. This calculation scheme is to be expanded in the future.

A systematic materials selection for autonomous shuttle systems as part of this research was published in [18]. Further research is necessary to assess innovative production and manufacturing technology regarding their suitability.

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