Linköping University | Department of Management and Engineering
Master's thesis, 30 hp | Design and Product Development
Autumn 2018 | LIU-IEI-TEK-A--18/03301—SE

Compact lifting mechanism of autonomous vehicle

– Concept development and guidelines for implementation

Fredrik Engström
Rasmus Andersson

Supervisor: Micael Derelöv
Examiner: Mikael Axin

Linköpings universitet
SE-581 83 Linköping, Sverige
013-28 10 00, www.liu.se

Authors:

Fredrik Engström
M.Sc, Student within Product Development specializing in Technical Design
Linköping University | Sweden
Fredrik__Engstrom@hotmail.com

Rasmus Andersson
M.Sc, Student within Mechanical Engineering specializing in Product Development
Linköping University | Sweden
rasmus.andersson_@outlook.com

Supervisors:

Peter Tengvert
Principal Engineer ICR
Toyota Material Handling Manufacturing Sweden | Sweden
Peter.Tengvert@toyota-industries.eu

Micael Derelöv
Senior Lecturer
IEI | Division of Machine Design
Linköping University | Sweden
Micael.derelov@liu.se

Examiner:

Mikael Axin
Senior Lecturer
IEI | Division of Machine Design
Linköping University | Sweden
Mikael.axin@liu.se

Abstract

The material handling industry is facing new challenges with the divergence from the established EUR-pallet. In correlation with the autonomous technology which is becoming more advanced, available and affordable than ever before, new demands are created. The industry calls for innovative material handling automated guided vehicles to meet the requirements. These vehicles will increase the owners profit by being more efficient in terms of time, size and cost. The aim for this study is to develop suitable lifting mechanisms for an ultra-compact automated guided vehicle. A generic product development process is utilized. The requirements for the lifting mechanism is defined and presented in a specification. A selection of employees are involved in the ideation and concept generation to add in-house knowledge and experience. The concepts are developed with component research, 3D visualizations and concept descriptions. The concepts are evaluated and the most promising are selected. The selected concepts are further developed with CAD-models, calculations and a selection of components. The concepts are compared with each other and the initial specification to assess the most suitable lifting mechanism. The single acting hydraulic system, including a Micro Power Pack and four small hydraulic cylinders, is considered the best suitable choice for an ultra-compact material handling automated guided vehicle.

Acknowledgments

We would like to thank our supervisors at Toyota Material Handling Manufacturing Sweden, Peter Tengvert and Boris Ahnberg, for their commitment and for giving us such a great responsibility in a customer-based project. Thanks to all the employees at the development unit for showing great interest in our project and for answering all our questions. We would also like to thank Micael Derelöv, our supervisor at Linköping University, for guidance and insights, as well as our examiner Mikael Axin for his support. Lastly, we would like to thank our opponents Filip Andersson and Niklas Martinsson for reflections and valuable feedback.

Linköping December 2018

Fredrik Engström
Rasmus Andersson

Table of Contents

List of Figures

Nomenclature

AGV –Automated Guided Vehicle.

Air Lift – Manufacturer and supplier of air suspension and air management systems.

Box volume – Volume of the cuboid that encloses a component

BT – “Bygg och Transportteknik”, the Swedish forklift and pallet truck manufacturer is merged with Toyota Material Handling Europe in 2006 and becomes Toyota Material Handling Manufacturing Sweden.

FEM - Finite element method (Software used is Structural Analysis in CATIA.V5 by Dassault Systèmes)

Hydro Power Transmission – Swedish supplier of hydraulic systems

IMI Precision Engineering – A world leader in motion and fluid control technologies

LINAK AB – A Swedish manufacturer of electric linear actuators and lifting pillars.

Proof-of-concept prototype – A proof-of-concept prototype can complete all or a selection of the final product’s tasks or functions in a regulated manner and environment.

Sectioning of system – The system consists of several separable sections rather than one coherent piece.

Test-rig Prototype – A prototype designed to test one or several functions in a controlled environment.

TMHE – Toyota Material Handling Europe

TMHMS – Toyota Material Handling Manufacturing Sweden, the site located in Mjölby.

Ultra-compact AGV – The most compact AGV yet to be developed by TMHMS

1 Introduction

1.1 Company Background

Toyota Industries Corporations (TICO), the parent company, is the global number one in material handling since 2001 with its 52,600 employees. Toyota Material Handling Group (TMHG) is one of the key business divisions with 32,500 employees. See organization chart Figure 1.

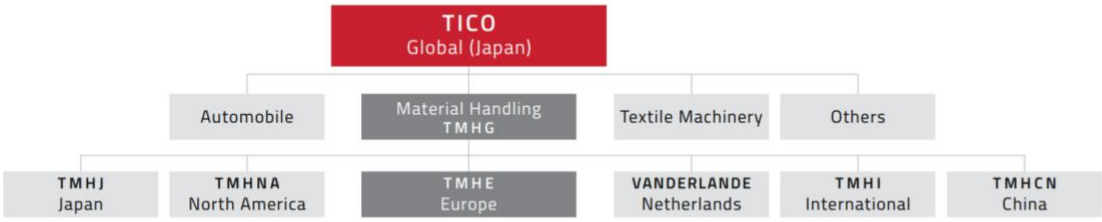


Figure 1 Toyota Industries Corporation (TICO) organization chart [1]

The aim is to provide customers with an entire business solution. They offer finance, rental, spare parts, machine service, operator training and management support. Toyota Material Handling Europe (TMHE) with its branch Toyota Material Handling Manufacturing Sweden (TMHMS) is a consolidation with BT, a successful pallet truck manufacturer who developed the EUR-pallet. With more than 80 years of experience they have developed a lot of pallet handling solutions. Hand pallet trucks, powered pallet trucks, powered stackers and reach trucks are some products from their wide product selection, see Figure 2. They also offer costumer adapted solutions. [1]

Figure 2 A selection of products manufactured at TMHMS [1]

TMHE offers different types of automated solutions to optimize efficiency and minimize property damage and labor costs. Such as automated carts, powered pallet trucks and load carriers, see Figure 3. Currently there is a smaller scale production of these automated products. By adopting to new technology and focus on future customer needs, TMHE strive to keep their leading market position. [2]

Figure 3 A selection of TMH's automated solutions [2]

1.2 Problem Background

Material handling is a collection name for the activity of handling objects. Material handling demands logistics which can be explained as the knowledge to manage flows of resources. To achieve an efficient material handling system, a structured plan and accurate execution is required.

To increase the efficiency, supporting vehicles, software's and other types of aid have been developed. The most common aid in the material handling industry is the EUR-pallet. The EUR-pallet serves as a platform for an endless variety of cargo. Regardless of cargo the EUR-pallet can easily be moved with a pallet handling solution. However, the EUR-pallet has some disadvantages such as a relatively high weight and bulky size. The EUR-pallet is not suitable for smaller objects and does not maximize space in shipping containers or trucks. To increase efficiency and simplify handling different alternatives have been developed.

An alternative to the EUR-pallet is a custom pallet made of corrugated cardboard. These pallets only weigh 1kg instead of 25kg and they are half the height of a EUR-pallet. These pallets maximize the vertical space in trucks and reduces the total weight handled. As an alternative to pallets different kinds of carts and roller containers have been developed. This to make it possible to handle cargo without external assistances such as hand pallet trucks or forklifts.

Manual human-based labor is often costly and have limitations in speed and capacity, thus a desire for automated solutions exist. The individual customer, autonomous vehicles and alternative energy sources will affect how material will be handled in the future. The technologies for highly advanced robotics and logistic centers are already available, but the market is not ready. The customer desires to implement automated solutions to their existing infrastructure rather than building new state-of-the-art facilities.

For the Automated Guided Vehicle, AGV, manufacturers, such as TMH, it is not favorable in terms of resources to create specific material handling solutions for each individual customer. The manufacturers want to create universal AGVs' applicable to every specific situation, thus the product criteria must correspond to the most restrictive demands. The most common requirement is the one of size. Smaller AGVs' allows more space for material to be handled resulting in higher capacity.

AGVs' include subsystems such as drive units, control units, sensors, lift mechanism and batteries. To create an ultra-compact AGV these subsystems must be carefully disposed in the given volume. New technical solutions are required to achieve the goal. TMHMS requests to know what technical solution of a lifting mechanism that is best suited for an ultra-compact AGV, thus a product development project is desired.

1.3 Purpose

A new technical solution of a lifting mechanism is required to meet the demands of autonomous material handling. TMHMS requests to know what technical solution is best suited for an ultra-compact AGV.

1.4 Objective

The objective is to develop concepts of lift mechanisms suited for an ultra-compact AGV. Several concepts will be evaluated to acquire knowledge of the technical solutions. The concepts will be developed with the support of in-house knowledge and experience.

1.5 Formulation of questions

The following questions are studied in the thesis:

Q1. What concept of a lifting mechanism is potentially best suited for an ultra-compact AGV?

Q2. From a general perspective, which factors are affecting the development of a product where space is restricted?

Q3. How can in-house knowledge contribute to the development of a technical solution?

1.6 Delimitations

1. Aspects of mass production, life-span and environmental impact will not be investigated.

2. Power sources will not be explored since a 24V lithium-ion battery is standard.

3. The ultra-compact AGV proof-of-concept prototype will not be built within the timespan of the master's thesis project.

4. Motor control units suitable for the concepts will not be presented since it is dependent of other sub-systems and determined by another project group.

1.7 Report Outline

2. Theory
- This chapter describes the theory of thechnical principles and methods which are used in the report

3. Methodology
- This chapter describes the methodology of the thesis in chronological order

4-8. Implementation
- These chapters includes a problem description and then the work from ideation via concept development to concept selection

9. Verification
- This chapter includes a comparison of the developed concepts together with a discussion.

10. Results
- In this chapter the selected concepts are presented

11. Discussion
- In this chapter the implemented methods are evaluated

12. Conclusion
- This chapter answers to the purpose and the research questions.

13. Further development
- This chapter decribes the further development of the most suitable concept.

2 Theoretical frame of reference

2.1 AGV/AGVS

Automated Guided Vehicle, AGV, is described as an unmanned vehicle used to transport objects. One AGV is exclusively working as a part of a system often referred to as Automated Guided Vehicle System, AGVS. An AGVS can be divided into four sub-systems; Vehicles, Stationary control system, Peripheral components and On-site components. These elements are essential for an efficient material handling system. [3] [4]

1. **Vehicles** are the actual AGV which transport the objects.
2. **Stationary control system** is administrating the communication with other systems. It also handles the customer interaction such as graphical visualizations and statistical analyses.
3. **Peripheral components** represent on-board equipment on the vehicle. Such as battery loading stations and load transfer mechanisms.
4. **On-site components** refer to the structural design on the environment that affect the AGV as for example ground, gates and lifts.

AGVS have existed for more than fifty years and were initially used in manufacturing systems. Technical advances such as improved actuators, energy supplies, new sensors and computer systems have been made. This has led to implementation of AGVS in many industrial branches such as goods transportation in warehouses, food processing, aerospace and port facilities.

Automation of previous mentioned industrial branches is a key point in the optimization of logistics. AGVS provides several benefits to fulfill this task. In relation to automatic static material handling systems such as roller or chain conveyors the advantage of AGVS is that it provides flexibility regarding integration in existing or changing environments. One of the goals of an AGVS is to be able to integrate it in the present systems with as few changes of the facilities as possible. [4]

The peripheral components can be varying from different AGVS, it can for example be the pulling device of the towing AGV, left in Figure 4, or the forklift function of the Lifting AGV. It can generally be described as all extra components to fulfill the required function besides autonomous transportation, maneuvering and the control function. [2]

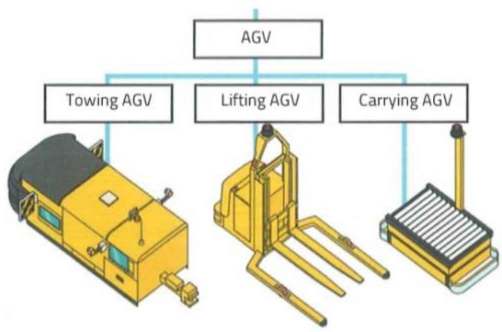


Figure 4 Automated guided vehicle types [2]

2.2 Technical principles

Following technical principles have been studied during the thesis.

2.2.1 Hydraulic system

A hydraulic system uses incompressible liquids as transmission media to transport energy from one location to another. A hydraulic system consists of several components such as reservoir, filter, pump, electric motor, pressure regulation valve, control valve, hydraulic cylinders, tubing and liquid, see Figure 5. The incompressible liquid is drawn from a reservoir by the pump and supplied to the cylinder. Hydraulic systems will most likely leak fluid and that lead to less efficiency and contamination of surrounding components. [5] A hydraulic Power Pack is a complete hydraulic system formed as a compact mobile unit.

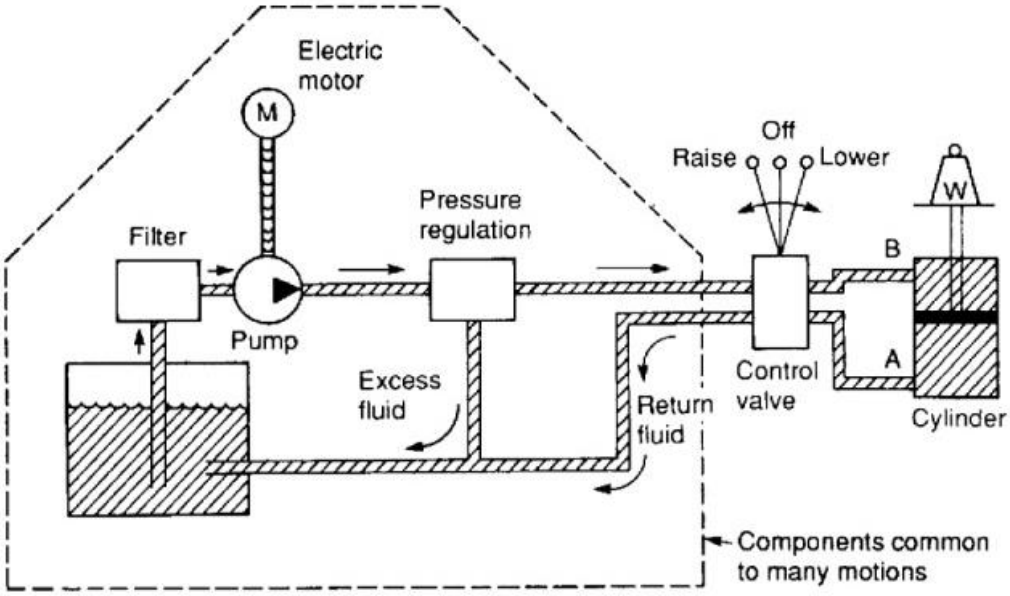


Figure 5 A generic hydraulic system [5]

Hydraulic cylinders are well suited for high-force applications and can hold the force and torque constant without supplying more fluid or pressure, due to the incompressibility of the liquid. The moving part of the hydraulic cylinder is the piston inside the cylinder. In a single acting system, the piston is returned to its original position either by a spring, fluid being sucked or by gravity. In a double acting system, the piston is returned by fluid being supplied to the other side of the piston, see Figure 6. Different hydraulic cylinders are used for single acting and double acting systems. The double acting system requires twice as many tubes since each hydraulic cylinder requires two. [6]

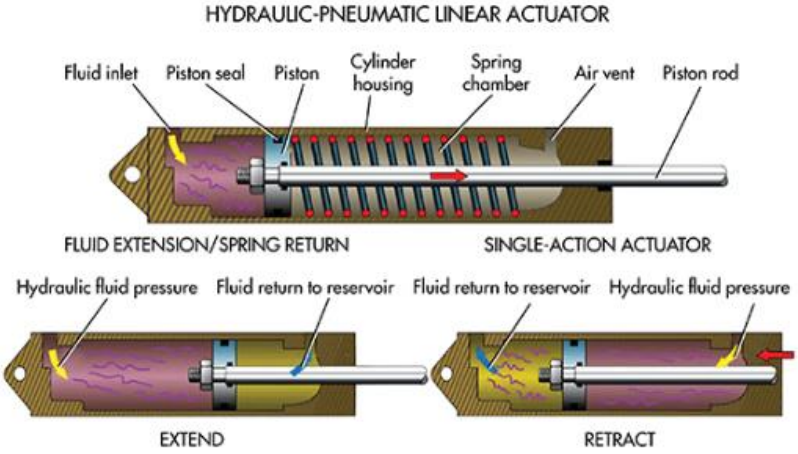


Figure 6 Hydraulic-pneumatic linear actuator [6]

2.2.2 Pneumatic system

A compressor driven by an electric motor pressurize air drawn from the atmosphere. The temperature of the air is increased by the compressor and requires to pass through a cooler and air treatment unit. An air reservoir store pressurized air to increase the speed of the pneumatic cylinder or air bellow movement. When the pneumatic cylinder or air bellow is retracted the air is released back to the atmosphere, see Figure 7. [5]

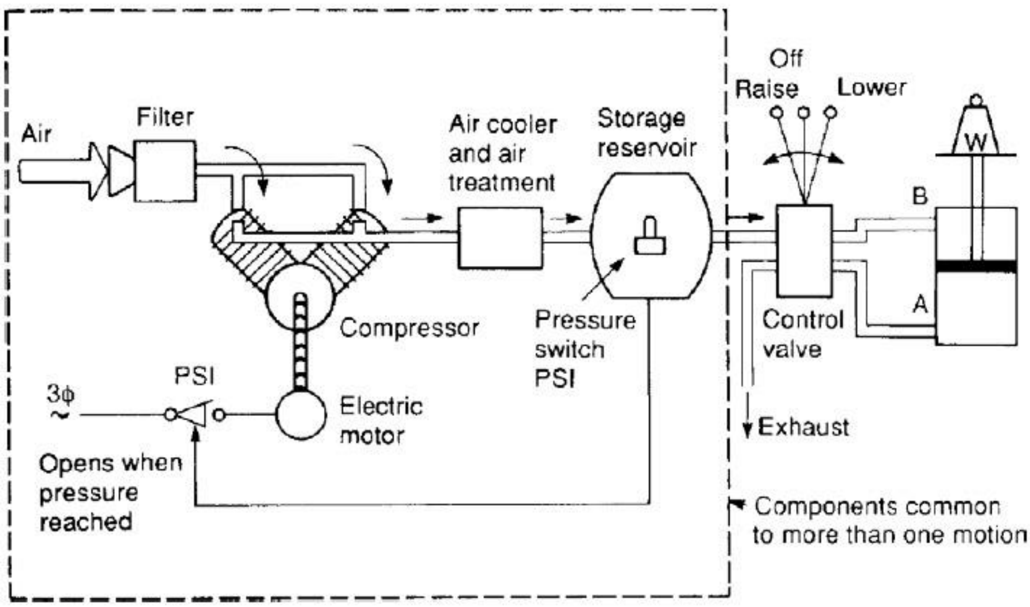


Figure 7 A generic pneumatic system [5]

Pneumatic linear actuators

Pneumatic linear actuators operate like hydraulic linear actuators, but with pressurized air. Pneumatic actuators generate precise linear motion and can generate a force relative to its size. Pressure losses and continually compressor run will lead to less efficiency than other linear-motion methods. The pneumatic cylinder needs to be designed for a specific job and cannot be modified for different loads. The advantages are miniaturization, low cost, lightweight and the accessibility of air. [6]

Air bellows

Air bellows are used as suspension in vehicles as replacement of regular coil springs and as air actuators in amusement park rides and scissor lifts. The coil spring or linear actuator is exchanged for a rubber membrane which can inflate and deflate as desired with the connected compressor system. Common air bellows are rolling lobe air bellows and convoluted air bellows which are configured in open or closed air suspension systems. The rolling lobe air bellow is considered simple in structure and low in cost. The rolling lobe air bellow, as seen in Figure 8, consists of a top plate, a bottom support and a rubber membrane. When deflated the rubber membrane folds around the bottom support. [7]

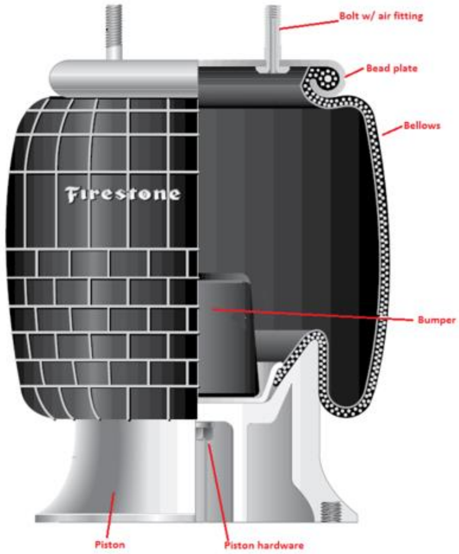


Figure 8 Rolling lobe air bellow from Firestone [7]

The convoluted air bellows have one or several convolutions on top of each other, as seen in Figure 9. Multiple convolutions are added to increase stroke length. [7]

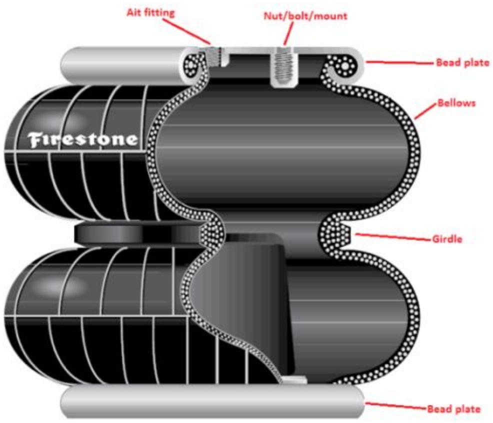


Figure 9 Convoluted air bellow from Firestone [7]

2.2.3 Electric linear actuator

Electric linear actuators convert electrical energy into torque in a motor. A gear connected to a lead screw mechanically transforms the torque into a linear force of a nut. The nut is prevented from rotating with the lead screw and therefore moves linear, see Figure 10. Electrical actuators offer high precision of position up to ±0,008mm, and generate linear movement of both push and pull loads. [6] Electrical actuators can be integrated in complex systems and can be used with databus communication. Accurate feedback of position and control of acceleration and velocity is possible. Easy to install and low/no need of service. [8]

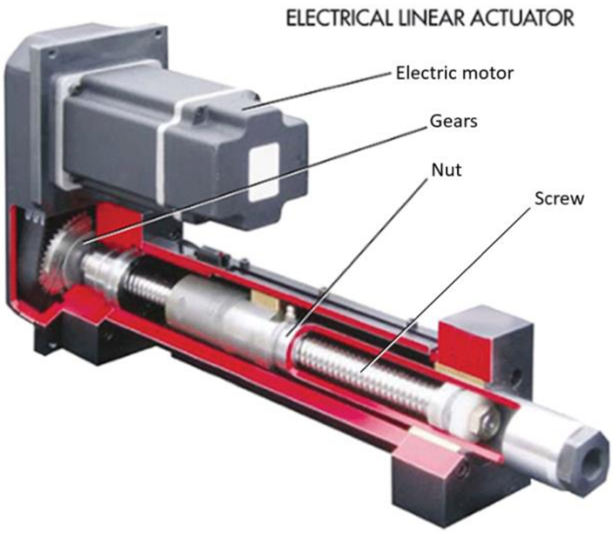


Figure 10 Electric linear actuator [6]

2.2.4 Shape memory alloys

Shape memory alloys (SMA) are materials with two distinct crystal structures, martensite and austenite. At lower temperatures, the alloy is martensitic and can then easily be deformed into any shape. As the alloy is heated it transforms into austenite phase and the alloy retains its previous form. Austenite is not stable at room temperature and therefore it transforms into martensite again. This phase alteration gives shape memory alloys super-elasticity properties. [9]

Shape memory alloys are used in many applications, most common thermostats. A SMA manufacturer, has developed both springs and wires from SMA that gives a heat activating product that generates force. Those are used as small thermal actuators which activates by heat or electricity. The force generated is relatively high compared to the size 0,3-118N for the wires which are 0,025-0,5mm thick and 2-50N for the springs which are 3-14mm in diameter and have a stroke up to 30mm. [10]

2.2.5 Electromagnets

Electromagnets is made from a core of magnetic material surrounded by a coil. When current is passed through the coil it magnetizes the core. The core then attracts other magnetic materials. The strongest attraction-force is when two magnetic materials are in contact. When the materials are separated the attraction-force decreases and when they are far away from each other there is no force. The force varies relative to current and number of turns on the coil.

A solenoid is a type of electromagnet with an iron frame enclosing the coil and a cylindrical plunger moving inside the coil. This acts like an actuator that produces mechanical force when electric current passes through the coil. Due to differences in the distance of the plunger and frame solenoids generates a force which alternates during the stroke. [11]

2.3 Method of product development process

Following methods have been studied in the thesis.

2.3.1 Generic product development process

The generic product development process according to Ulrich and Eppinger consist of six phases, as seen in Figure 11. A structured product development process is needed to assure quality, coordinate resources, follow a time plan and create documentation to collect acquired knowledge. [12]

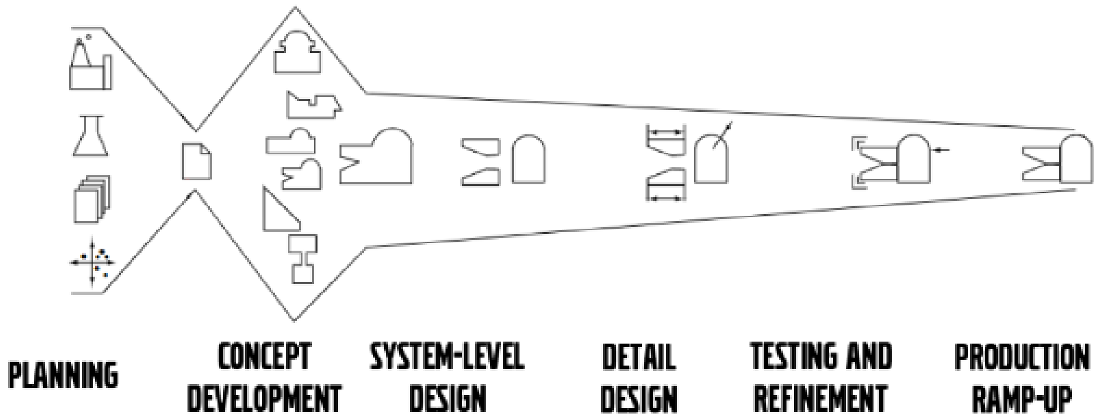


Figure 11 Generic product development process [12]

Planning
The planning phase is the connection between advanced research and technology development activities. The output of the planning phase is a mission statement and contains a specification of target market, business goals, key assumptions and constraints.

Concept Development
The first step of concept development is to identify the needs of the target market and of the costumer. The customer needs are then interpreted by engineers into measurable detail of what the product must do and formulated in the product specification. A specification consists of a metric and a value such as “average lifting time” and “less than 4 seconds”. The product specification is several individual specifications together. When a product specification is set, a wide variety of product concepts are generated, evaluated and one

or more concepts are selected for further development and testing. A concept is an approximate description of the form, function and features.

System-level Design

When one or more concepts have been selected, the next step is to define the product architecture, break down the concept into sub-systems and components and initiate preliminary design of key components. The concept is then built up with a geometric layout of the product and functional specification of the products subsystems.

Detail Design

In the detail design phase, the specification of geometry, materials and tolerances are set. A control documentation consists of drawings or computer files to describe the geometry of each part.

Testing and Refinement

The carefully designed concept is constructed and evaluated as a preproduction version of the product. Prototypes are usually built, but not necessarily by the same means of the intended production, to determine if the product will work as designed.

Production Ramp-up

In this phase, the product is made by the intended production system. The purpose of the production ramp-up is to train the workforce and solve any remaining problems.

2.3.2 Brainstorming

Brainstorm is a method used in creative thinking to generate many ideas. The method brainstorm can be used throughout all phases of the design process but is considered more favorable when starting up the generation of ideas to solve problems which are relatively simple. The brainstorm should be performed as a session with 4-15 participants and a facilitator. During the brainstorming session, a set of strict rules must be applied:

1. **Criticism is postponed.** During the brainstorm, bad ideas does not exist. Participants should not think of feasibility, utility, importance or attack or overrule other's suggestions.
2. **Freewheeling is welcomed.** A safe and secure atmosphere must be created to encourage participants to express every idea that comes to mind.
3. **1+1=3.** Combinations and improvements of ideas are sought.
4. **Quantity is wanted.** The method assumes that quantity leads to quality.

Before the brainstorming session the facilitator should define the problem and develop a problem statement. The facilitator then begins the session by explaining the method with associated rules and starts off with a warm-up round. Then a presentation of the problem statement is done followed by the main generating of ideas which the facilitator writes down on a flip chart. Once many ideas have surfaced the group should select the most promising and interesting ideas and cluster according to some relevant criteria. The clusters of ideas should be evaluated and a selection of which ideas to bring further in the design process is done. [13]

2.3.3 Brainwriting and Brain Drawing

Brainwriting and brain drawing are alternatives to the brainstorm method. These methods follow the same set of rules and overall approach, see the section on brainstorm above. Brainwriting and brain drawing are carried out on sheets of paper which are passed around the participants so that they can build upon each other's ideas. The number of participants should be 4-8. The main difference is that Brainwriting emphasizes written ideas and brain drawing, drawn ideas. Before the session, the facilitator should define the problem and develop a problem statement. The facilitator brings plenty of A3 and A4 sheets of paper together with pens, pencils and markers and then begins the session by explaining the method with associated rules and starts off with a warm-up round. Then a presentation of the problem statement is done followed by the corresponding method:

1. **Brainwriting 6-5-3 method.** Each participant (six in this case) writes down three ideas in a time span of five minutes. After five minutes, the papers are passed on to the next participant to be elaborated or used as inspiration for the next three ideas. This should be repeated five times to create 90 ideas in 25 minutes (6 people x 3 ideas x 5 rounds = 90 ideas)
2. **Brain drawing.** For three minutes, each participant draws one idea on a sheet of paper. After three minutes, the paper is passed on to the next participant who adds drawings or ideas to the initial drawing. This procedure is repeated several times.

Once many ideas have surfaced the group should select the most promising and interesting ideas and cluster according to some relevant criteria. The clusters of ideas should be evaluated and a selection of which ideas to bring further in the design process is done. [13]

2.3.4 Design Workshops

A design workshop is a creative participatory co-design method where the ideas and insights from the participants are sought. A design workshop can engage stakeholders to gain a creative trust and, in a fun, efficient and compelling way get their input. Design workshops generally consists of several activities and techniques such as mapping, diagramming, mock-up creation and sketching which are carefully planned and executed by design team facilitators. The most crucial feature of the workshop is to plan the timing and logistics for the session and keeping to the plan during the session but at the same time be adaptable for changing circumstances. Insights and ideas are collected during the session as well as activity outcome afterwards. The number of facilitators should be relative to the number of participants and each facilitator should have a clearly defined role. [14]

2.3.5 Prototyping

A prototype is a physical representation of a product or concept and can be seen as a creative translation of research or an ideation. Prototypes are categorized according to level of refinement or fidelity. Low-fidelity, Lo-Fi, prototypes are common in early ideation processes and serves for internal development purposes and suitable for early testing of ideas. A Lo-Fi prototype can for example be a concept sketch, a storyboard or a sketch model. High-fidelity, Hi-Fi, prototypes, often represents the final product in look and feel and sometimes even function, thus more refined. Hi-Fi prototypes are more common in the later phases of product development. Examples of Hi-Fi prototypes are CAD-models and sophisticated physical models. Test rigs can be made with different level of refinement and be used to evaluate functionality. [14]

2.3.6 Concept screening and scoring

Concept screening, also called Pugh concept selection seen in Figure 12, is a method for narrowing down the number of concepts and to further understand and improve the concepts. The first step is to define a list of selection criteria and create a matrix. These criteria are chosen based on customer and company needs. The number of selection criteria is important and should be selected with caution. Too many unnecessary criteria will lead to less effective outcome. A reference concept is chosen, against which all other concepts are rated. The reference can either be an industry standard or a straightforward concept. Rate the concepts with “better than” (+), “same as” (0), “worse than” (-) for each selection criteria and summarize the score. The ranking of all concepts will show each concept’s potential and one or more concepts should be selected for further development. It is important to reflect over the selection criteria and to modify if needed. Adjustments of concepts and combinations of concepts could make new better concepts. It is important that the concepts are at the same level of abstraction and that the team members do not have biased interest in one or more concepts.

	Concepts						
Selection Criteria	**A Master Cylinder**	**B Rubber Brake**	**C Ratchet**	**D (Reference) Plunge Stop**	**E Swash Ring**	**F Lever Set**	**G Dial Screw**
Ease of handling	0	0	–	0	0	–	–
Ease of use	0	–	–	0	0	+	0
Readability of settings	0	0	+	0	+	0	+
Dose metering accuracy	0	0	0	0	–	0	0
Durability	0	0	0	0	0	+	0
Ease of manufacture	+	–	–	0	0	–	0
Portability	+	+	0	0	+,	0	0
Sum +'s	2	1	1	0	2	2	1
Sum 0's	5	4	3	7	4	3	5
Sum –'s	0	2	3	0	1	2	1
Net Score	2	–1	–2	0	1	0	0
Rank	1	6	7	3	2	3	3
Continue?	Yes	No	No	Combine	Yes	Combine	Revise

Figure 12 Concept Screening [12]

Concept scoring see Figure 13, is suitable when the concepts are more detailed. A similar matrix as concept screening is used. With more knowledge of the concepts the selection criteria list can be more thoroughly described. The selection criteria list is then assigned weighted factors by importance. Either by linear numerical scale or relative by percentage. Each concept is then rated compared to a reference concept for each selection criteria in scale (1)-(5). “Much worse” (1), “worse” (2), “same as” (3), “better” (4), “much better” (5). The ranking of concepts is done by multiplying weight factor with rating for each selection criteria. This gives a weighted score which is then summarized to a total score. The concept with the highest score is considered the best concept. [12]

A sensitivity analysis can be done by varying the weight factors of the criteria and analyze the effect on the ranking. A sensitivity analysis verifies if a ranking is adequate.

		Concept							
		A (Reference) Master Cylinder		DF Lever Stop		E Swash Ring		G+ Dial Screw+	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Ease of handling	5%	**3**	0.15	3	0.15	4	0.2	4	0.2
Ease of use	15%	**3**	0.45	4	0.6	4	0.6	3	0.45
Readability of settings	10%	2	0.2	**3**	0.3	5	0.5	5	0.5
Dose metering accuracy	25%	**3**	0.75	3	0.75	2	0.5	3	0.75
Durability	15%	2	0.3	5	0.75	4	0.6	**3**	0.45
Ease of manufacture	20%	**3**	0.6	3	0.6	2	0.4	2	0.4
Portability	10%	**3**	0.3	3	0.3	3	0.3	3	0.3
	Total Score	2.75		3.45		3.10		3.05	
	Rank	4		1		2		3	
	Continue?	No		Develop		No		No	

Figure 13 Concept Scoring [12]

2.3.7 Business feasibility aspects

The product development process in an expensive process and its necessary to in a qualitatively way chose concepts that have the greatest potential for marketing success. An article about product development describes a concept evaluation method for selecting innovative concepts with greater potential marketing success. One part of this method is to evaluate business feasibility to meet the firm´s characteristics and its interests. In this way, the concept evaluation will lead to a more realizable concept. Aspects to be included in the concept evaluation are following: [15]

- Maturity of the technology
- Knowledgebase in-house
- Complexity of manufacturing and assembly
- Manufacturing methods
- Knowledge of the market
- Economic efficiency

3 Methodology

This chapter describes the methodology of the thesis in chronological order. The methods are described in chapter 2.3.

3.1 Problem description

To specify the problem and generate a foundation for the product development process a vision of how the final product should work was established. From the vision, product requirements arose. The information was then processed into a **Target Specification** which focused on the lift mechanism. The project framework was then investigated.

3.2 Ideation and Concept Generation

A wide variety of ideas and concepts were explored. Several **Workshops** with appropriate representatives from TMHMS as participants were collecting inhouse knowledge, insights, ideas and concepts of lift mechanisms. The Workshop was carefully planned with **Brainstorming** and **Brain writing** activities to ensure creativity and commitment. The ideations were categorized according to similarity, technical principle, function means, supporting functions and visualized in a function means flow chart. With the overview from the function means flow chart the participants ranked the different solutions in a follow-up meeting according to a set of criteria. 9 concepts were after the ranking considered promising and were further developed.

3.3 Concept Development

The concepts were developed to make a structured and thoroughly objective concept selection. The concepts were equally evolved for just comparison and therefore developed by following areas:

Available components
A research for available components provided insights of the concepts level of feasibility. This research resulted in an initial suggestion of suitable components.
3D visualization
3D visualizations were created to declare the geometrical features of the concepts. These visualizations were created in CATIA V5. Where the concepts were existing products a picture were presented.
Concept information
To provide an overview of the concept a description of the concept was created. It described the properties of the concept quantitatively and included initial calculations.

3.4 Concept Evaluation & Selection

An unbiased concept selection was achieved by utilizing **Concept Screening & Scoring** on equally evolved concepts. To implement the method a list of selection criteria was established. The list of criteria was used to compare the concepts. The concept selection was done together with the supervisors at TMHMS. A sensitivity analysis was done to validate the ranking.

3.5 Conceptual Design

The chosen concepts from **Concept Screening & Scoring** was then further developed and described by a system level design approach. When system components were identified, suppliers were contacted to configure wanted components. Mechanical parts were 3D-modeled in CATIA V5 and FEM-calculated. A system layout of the lifting mechanisms was created to visualize placing and volume occupation. In-house knowledge was used to verify the concepts.

3.6 Verification

The concepts were evaluated against the **Target Specification** and then against each other to assess which concept is best suited for the ultra-compact AGV.

4 Problem description

A vision of how and for what customer the final product will work was established through an introductory meeting with the supervisors at TMHMS. The need for a compact lift mechanism appeared from an inquiry from an international customer. The customer requested a large amount of AGVs in a size that TMH does not yet offer. TMHMS as a leading operator in the industry of material handling identified that if the requirements obtained by the customer was modified, a reduction of size, the AGV can be used for a huge customer segment. Therefore, TMHMS formed a product specification for an ultra-compact AGV and assigned a development team for the project.

The project is in the state of developing a proof-of-concept prototype. A proof-of-concept prototype can complete all or a selection of the final product's tasks or functions in a regulated manner and environment. The proof-of-concept prototype is used in the organization to determine if the concept should be further developed into a fully functioning mass-producible product. The proof-of-concept prototype will be demonstrated in the spring of 2019. In this case two proof-of-concept prototypes will be created. One of the advantages of building two proof-of-concept prototypes is that different solutions can be tested for further evaluation. Thus, if two concepts of lift mechanisms are recommended for further development, both can be built and tested.

The product specification of the ultra-compact AGV was studied and the specifications which correlate to the lifting mechanism formed the Target Specification, see Table 1.

The dimensions of the ultra-compact AGV is 455x980x110mm which corresponds to a volume of $49dm^3$. All components and subsystems inside the AGV except for a lift mechanism occupies a volume of $25dm^3$. The remaining $24dm^3$ was mostly unusable volume between components. The usable volume was identified as several cuboid volumes, further mentioned box volume, which was approximated to $9dm^3$. The largest coherent box volume identified was $4{,}9dm^{3.}$ This means that the lifting mechanism must have a total box volume smaller than $9dm^3$ and that the largest component in the lift mechanism may not exceed $4{,}9dm^3$.

Table 1 Target Specification

ID	Description	Unit of measurement	Marginal value
1	Lifting height	Millimeter [mm]	35
2	Lifting time	Seconds [s]	2
3	Lowering time	Seconds [s]	2
4	Lifting weight	Kilogram [kg]	600
5	Height	Millimeter [mm]	110
6	Available volume for the lifting mechanism	Volume [dm^3]	9
7	Largest Coherent box volume	Volume [dm^3]	4,9

5 Ideation and concept generation

5.1 Workshop

To generate ideas of how to elevate an object, and to acquire in-house knowledge a workshop was held. A workshop is an easy, fun and creative way to collect this knowledge. Together with the supervisors at TMHMS, a list of suitable participants was established. Theories of workshops and associated activities were studied. A workshop setup was formed to fit the predefined participants and the wanted outcome, see Appendix A Workshop Plan for workshop details.

5.1.1 Test-workshop

A test-workshop was held with the main target to evaluate the method, a photo from the test-workshop is seen in Figure 14. The workshop was held with two participants who were chosen by their interest and enthusiasm rather than experience. After the test-workshop the different activities were discussed, and pros and cons were highlighted which resulted in readjustments for upcoming workshops. A by-product of the test-workshop was several useful ideas and concepts.

Figure 14 Photo taken during the test-workshop

5.1.2 Actual workshops

Two workshops were held to acquire in-house knowledge. Eleven participants were divided into two separate groups. Smaller groups gave each participant time and space to elaborate their own thoughts and the opportunity to comment on others. The workshop had three activities: warm-up, brainstorm and lastly a mix of brain drawing and writing, see Appendix A Workshop Plan for workshop schedule. The warm-up exercise encouraged the participants to be creative, open-minded, cheerful and free of self or external criticism. The brainstorm motivated the participants to focus about handling objects vertically and to broaden each individual's mindset of the subject. The third activity, brain drawing and writing, was shaped to acquire as many thoughts and as much knowledge from the participants on how to elevate an object as possible. The participants illustrated their ideas on paper which were then elaborated with discussions. Every idea was unfolded to the point that every participant understood the intention. If questions arose regarding feasibility, a participant with adequate knowledge or experience was consulted and notes were added to the illustrations.

The workshops resulted in a large quantity of ideas and concepts expressed as sketches with associated notes or written explanations, see a sample in Figure 15. The level of refinement varied from shallow ideas to elaborate concepts.

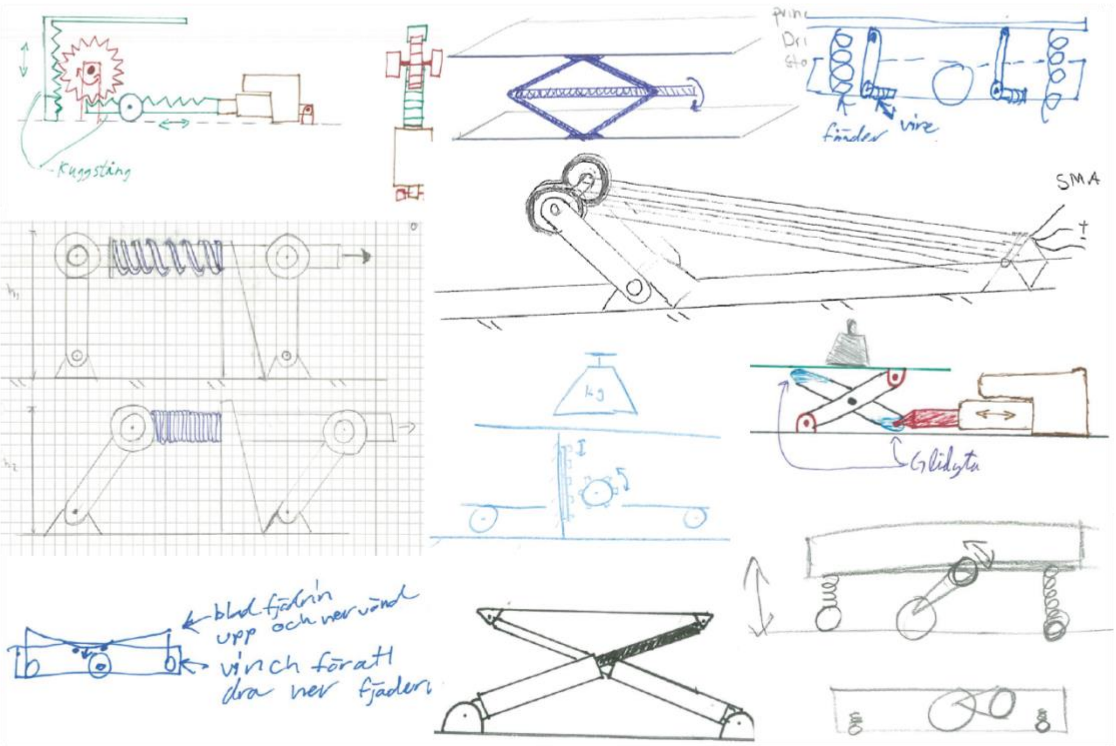


Figure 15 A sample of sketches from the workshops

5.2 Categorization

The outcome from the workshop were categorized into groups of technical principle, supporting functions and function means. Several function means and supporting functions were recurring for multiple technical principles. Graphic illustrations were made to better understand the ideas and to combine similar ones.

Shape memory alloys, an identified technical principle, was considered highly innovative but without any knowledge or experience. A brief research was done on the subject and the discovery that shape memory alloys could not be up-scaled to the theoretical required properties, see chapter 2.2.4. The technical principle shape memory alloy was removed from the selection.

To get an overview of the categorized ideas they were distributed in a function means flow chart, see Figure 16 for overview or Appendix B Function Means Flow Chart for full view. A quantity of close to 40 different ideas can be found in the function means flow chart.

Figure 16 Function means flow chart

5.3 Follow-up meeting

To choose the more promising ideas the workshop participators were summoned to a follow-up meeting. The function means flow chart was presented and the participators ranked the ideas by a set of criteria in a digital form, see Appendix F Follow-up Digital Form. The follow-up meeting was done in Swedish due to ease the communication and comfort of the participators. The criteria originate from the Target Specification and from what aspects that was during the Workshops considered as preferable for a lift mechanism. The ideas were ranked in a point-based system.

First, the technical principles were ranked relative to each other. The result was illustrated in a spider charts, see Figure 17.

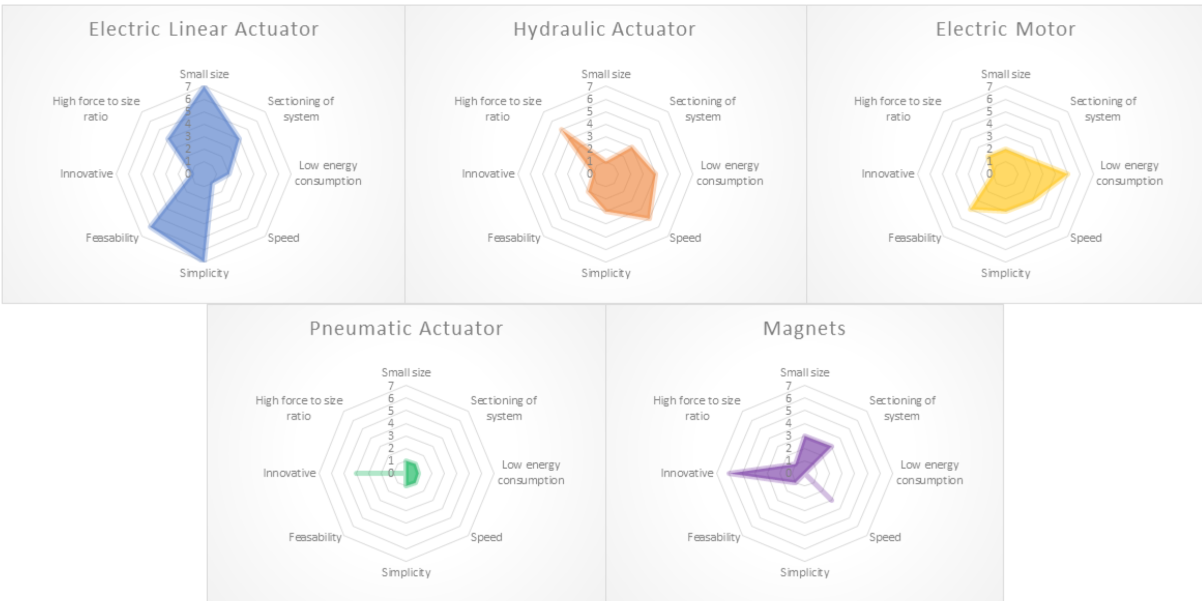


Figure 17 the result of the ranking of technical principles

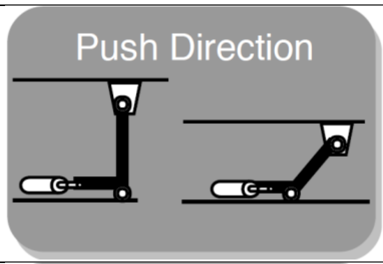
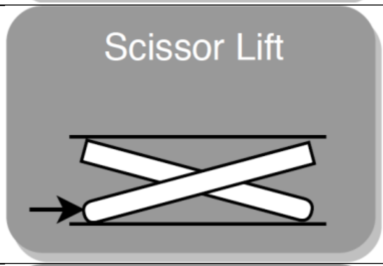
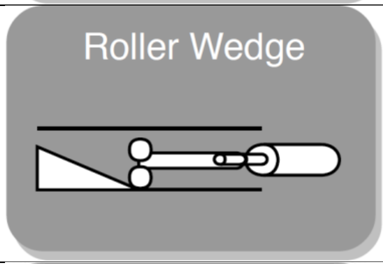
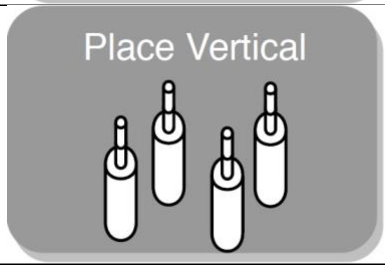
The ranking of technical principles was followed by the ranking of function means. During this ranking, the technical principles were not compared, but the function means associated with the same technical principle were. See Appendix C Ranking of Function Means for all rankings.

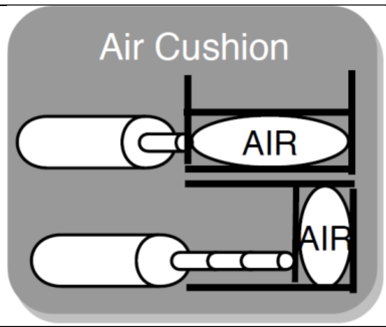
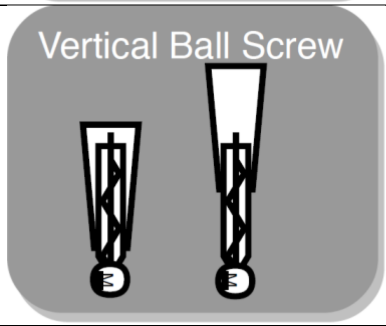
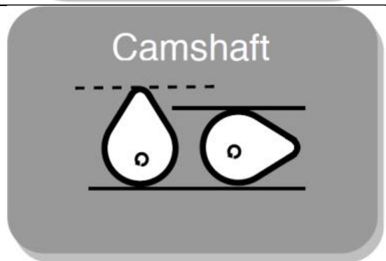
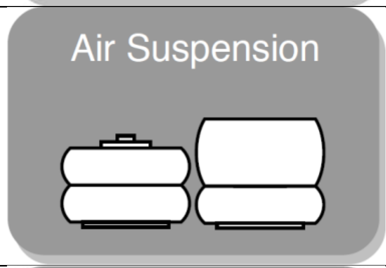
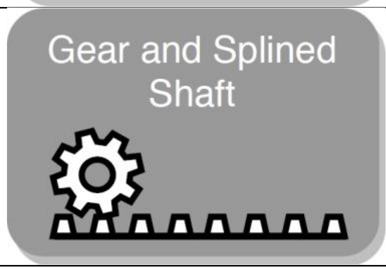
During the ranking of technical principles, a discussion of the adequacy of using magnets as a lifting mechanism occurred. The matter was discussed, and a case that magnets can produce a large force but only when in contact or in proximity of another magnet became crucial. As a lifting mechanism to lift 35mm the magnets would need to be extremely powerful, or the magnets would need to be lifted together with the cargo and a second lift mechanism was required. Solenoids tends to vary the actuating force and was not seen suitable. Therefore, magnets were not considered a possible solution.

The points for each function mean were summarized and the three highest ranked ideas for each technical principle were considered promising. For the technical specifications; electric linear actuator and hydraulic actuator, a fourth idea which was Place vertical passed through due to the simplicity of the concept. Since the function means which were associated to the same technical principle was compared and not between different technical principles some function means were essentially the same. These were: Place vertical, Push in new direction, Air cushion and Scissor lift. Even though different technical principles required different systems and components the function means were considered sufficiently similar to create combined initial calculations and design.

This resulted, after aggregation, in 9 concepts, see Table 2.

Table 2 The 9 concepts that came out of the Follow-up ranking

A. Push Direction An electric or hydraulic linear actuator applies a force on a brace which creates a lift.	
B. Scissor Lift An electric or hydraulic linear actuator applies a force on a scissor lift construction to create a lift.	
C. Roller Wedge An electric linear actuator pushes a carriage onto a wedge to create a lift.	
D. Place Vertical Place a linear actuator vertically. Electric linear actuators and hydraulic cylinders are interesting.	

<table>
<tr>
<td>E. Air Cushion
An electric or hydraulic linear actuator applies a force to an air-filled cushion to create a lift.</td>
<td>
</td>
</tr>
<tr>
<td>F. Vertical Ball Screw
An electric motor creates a rotation for a ball screw to create a lift.</td>
<td>
</td>
</tr>
<tr>
<td>G. Camshaft
An electric motor rotates cams to generate a camshaft principle lift.</td>
<td>
</td>
</tr>
<tr>
<td>H. Air Suspension
A compressor system fills air bellows to generate a lift.</td>
<td>
</td>
</tr>
<tr>
<td>I. Gear and Splined Shaft
A vertically placed spline shaft is attached to a lifting platform. An electric motor elevates the splined shaft.</td>
<td>
</td>
</tr>
</table>

6 Concept Development

Of the nine concepts that came out of the concept generation phase, concept **A. Push Direction** and concept **E. Air Cushion** needed elaboration before further development. Concept A was divided into two concepts, A1 and A2. From concept E a variant with a hydraulic solution appeared, concept E2, whilst concept E Air cushion remained as E1. Concept **I. Gear and Splined Shaft** was seen as a primitive solution of an electric linear actuator. To create a gear and splined shaft solution within the time limit which exceeds the performance of existing electric linear actuators was considered unreasonable and therefore excluded for further development.

The ten concepts were further developed by a research of available components, a concept specification including initial calculations and component specifications and by creating 3D CAD-models, see Table 3.

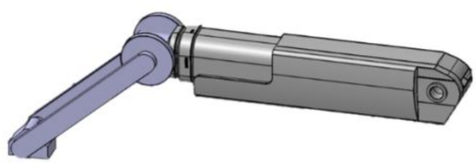
6.1 Concepts

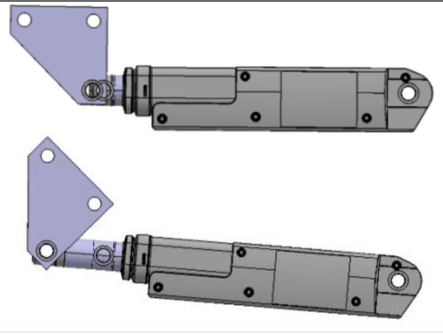
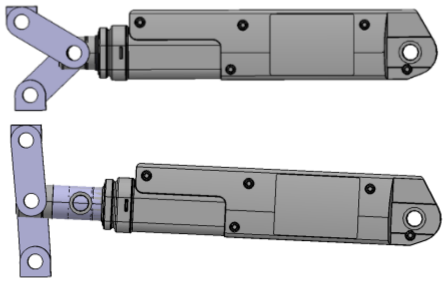
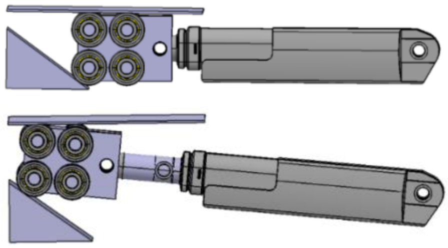
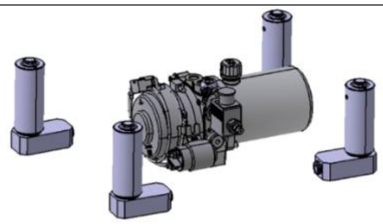
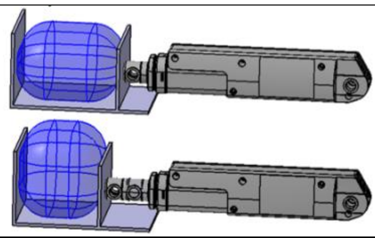
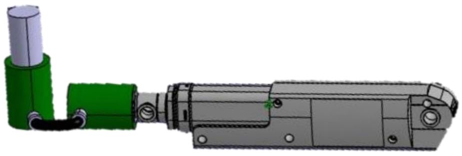
The research for available components started off by determining what components or subsystems the concept required. An initial research on the technical principle was performed. A technical principle is the mean which transforms the electric energy into a mechanical force, such as electric motors. A research for subsystem components was issued. Specifications of suitable components were documented, see Appendix E Component Research. For those concepts including electric linear actuators the actuator LA20, from the actuator producer LINAK, was used. A comparison between electric actuators was done and showed that LA20 was advantageous in several aspects, see Appendix D Concept Development. It had the smallest size of all identified electric linear actuators and with the force 2500N it produced the most force per volume unit. No other actuator was close to the performance of LA20 and the second best had twice the volume.

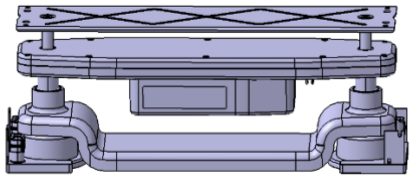
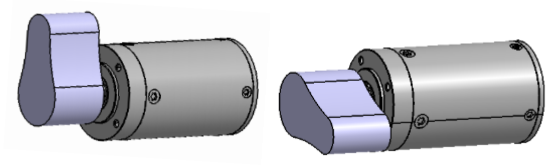
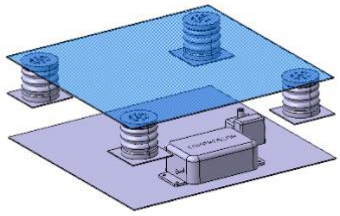
Some of the subsystems which could not be found on market was visualized by 3D-CAD models or drawings. These were then calculated by static mechanic theory to identify initial dimensions, restrictions and distribution of the concepts.

The concept development phase resulted in 10 concepts which are shortly described in Table 3, for complete information see Appendix D Concept Development.

Table 3 The 10 concepts for concept selection

A1. Push Brace An electric linear actuator applies a force on a connected brace. The length and angle of the brace determine the required force and stroke. If the angle is larger than 45° the leverage is advantageous. Two electric linear actuators of the type LA20 is required.	

A2. Push Lever An electric linear actuator pushes a lever mounted on a carrier. The dimensions of the lever determine the force transmission, thereby speed and stroke. Three electric linear actuators of the type LA20 is required.	
B. Scissor Lift An electric linear actuator pushes half a scissor lift. The length and angle of the scissors determine the required force and stroke. Four electric linear actuators of the type LA20 is required.	
C. Roller Wedge An electric linear actuator is connected to a roller wagon that is pushed onto a wedge. The rollers reduce friction. The angle of the wedge determines required force and stroke. Two electric linear actuators of the type LA20 is required.	
D. Place Hydraulic cylinder Vertical A hydraulic system with a Micro Power Pack supplies cylinders with hydraulic pressure. The required pressure and flow are relatively low compared to forklift applications.	
E1. Air Cushion An electric linear actuator applies a horizontal force to an air cushion which deforms the air cushion and distributes the air vertically and creates a lifting force.	
E2. Enclosed Hydraulic with Electric Linear Actuator An electric linear actuator applies a force on a horizontal hydraulic cylinder which is connected to a vertical hydraulic cylinder	

F. Vertical Ball Screw Vertical ball screws with included electric motor constitutes a lifting mechanism. A combination of electric motor and pitch of ball screw determine speed and force.	
G. Camshaft Electric motors turn cams to induce a lift. The electrical motor, gearing, cam design and cam amount determine speed and force.	
H. Air Suspension A compressor fills several air bellows with air. An air suspension solution suitable for cars should be sufficient.	

7 Concept Evaluation & Selection

7.1 Selection criteria weighting matrix

To evaluate the concepts, some selection criteria from the ranking in chapter 5.3 was used combined with new criteria and criteria related to business feasibility aspects. The business feasibility aspects were rewritten to be better suited. Maturity of technology and Knowledgebase in-house were combined to Knowledge of technology. Complexity of manufacturing and assembly became Complexity of interface. Manufacturing methods were rewritten as Complexity of prototype. Knowledge of the market and Economic efficiency was not included as it did not affect this phase of the development. The new criteria were Speed, Strength, Implement data capture, Lead time and Energy consumption.

To assign each criterion a weight factor, a profound discussion was held with the supervisors at TMHMS, where the weight matrix was filled out. The weight factor of each criterion was set by a relative percentage mentioned in chapter 2.3.6. An excel spreadsheet was used to compare each criterion against each other, see Table 4. The upper right values were set as 1 if the "row criterion" was more important than the "column criterion" and 0 if it was less important. The weight matrix showed that the lead time was considered most important and that was due to the deadline of the proof-of-concept prototype which occurs in the spring of 2019. Knowledge of technology was ranked low and therefore considered unimportant, thus excluded in the concept scoring.

Table 4 Weight matrix to determine criteria importance

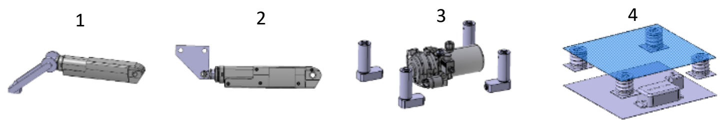
Weight matrix	Size	Sectioning of system	Speed	Strength	Knowledge of technology	Complexity of prototype	Implement data capture	Lead time	Energy consumption	Complexity of interface	Weight
Size		1	1	1	1	1	1	0	1	0	16%
Sectioning of system	0		1	1	1	0	0	0	1	0	9%
Speed	0	0		0	1	0	0	0	0	0	2%
Strength	0	0	1		1	0	0	0	0	0	4%
Knowledge of technology	0	0	0	0		0	0	0	0	0	0%
Complexity of prototype	0	1	1	1	1		0	0	1	0	11%
Implement data capture	0	1	1	1	1	1		0	1	0	13%
Lead time	1	1	1	1	1	1	1		1	1	20%
Energy consumption	0	0	1	1	1	0	0	0		0	7%
Complexity of interface	1	1	1	1	1	1	1	0	1		18%
											100%

7.2 Concept scoring matrix

When evaluating the concepts against each other the concept **B. Scissor lift**, highlighted in grey, was set as the datum reference because it was the most established solution. Due to lack of knowledge for each concept's energy consumption all values were set equal to the reference. The Concept scoring was completed together with the supervisors at TMHMS, which contributed with their knowledge and experience, see Table 5.

Table 5 Concept scoring matrix

Concept scoring											
Criteria / Concepts	Weight	A1	A2	B	C	D	E1	E2	F	G	H
Size	0,16	4	4	**3**	3	3	2	3	4	4	1
Sectioning of system	0,09	4	4	**3**	3	4	3	4	4	5	4
Speed	0,02	3	3	**3**	3	4	3	3	4	5	4
Strength	0,04	5	4	**3**	3	4	3	3	2	3	4
Complexity of prototype	0,11	3	3	**3**	3	3	2	2	2	2	2
Implement data capture	0,13	3	3	**3**	3	3	3	3	4	2	3
Lead time	0,20	3	3	**3**	3	3	2	2	2	2	5
Energy consumption	0,07	3	3	**3**	3	3	3	3	3	3	3
Complexity of interface	0,18	3	3	**3**	2	3	2	4	2	2	3
	Score	3,33	3,29	3,00	2,82	3,16	2,36	2,96	2,87	2,76	3,13
	Ranking	1	2	5	8	3	10	6	7	9	4
Much worse	1										
Worse	2										
Same as	3										
Better	4										
Much better	5										
Reference	3										



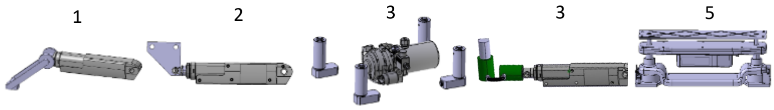
The concept scoring resulted in four solutions which were more promising than the datum. The electric linear actuator concepts A1 and A2 which were ranked as number one and two had both advantages of size and strength. The hydraulic system concept D was ranked as number three and had advantages of speed and strength but was larger than A1 and A2. The air suspension concept H was ranked as number four and had the largest advantage of the lead time since it consisted of available components on the market. The size of concept H was seen large because it needed an external compressor. A discussion led to the decision to further develop all four concepts as more information was needed to determine which concept that was best suited for the ultra-compact AGV.

7.2.1 Sensitivity analysis

To verify the result a sensitivity analysis was executed on the concept scoring. This was done by alternating the weights of the criterion in three different steps. First the criterion **Lead time** which had the highest weight factor of 20% was set to 0%. This to investigate what happened if the timeframe was longer. The result of this indicates that the concept H is sensitive for the **Lead time** and if time was not an issue this concept would not have been ranked high, see Table 6. Still it can be argued that it is an interesting technology. Otherwise the result was similar to the initial ranking, but it shows that the lead time have some impact on the results.

Table 6 Sensitivity Analysis 1

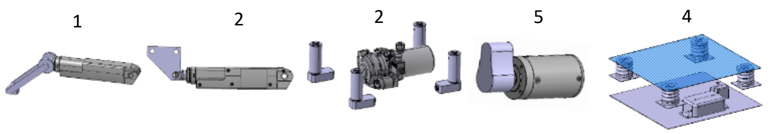
Concept scoring											
Criteria \ Concepts	Weight	A1	A2	B	C	D	E1	E2	F	G	H
Size	0,16	4	4	**3**	3	3	2	3	4	4	1
Sectioning of system	0,09	4	4	**3**	3	4	3	4	4	5	4
Speed	0,02	3	3	**3**	3	4	3	3	4	5	4
Strength	0,04	5	4	**3**	3	4	3	3	2	3	4
Complexity of prototype	0,11	3	3	**3**	3	3	2	2	2	2	2
Implement data capture	0,13	3	3	**3**	3	3	3	3	4	2	3
Lead time	-	3	3	**3**	3	3	2	2	2	2	5
Energy consumption	0,07	3	3	**3**	3	3	3	3	3	3	3
Complexity of interface	0,18	3	3	**3**	2	3	2	4	2	2	3
	Score	2,73	2,69	2,40	2,22	2,56	1,96	2,56	2,47	2,36	2,13
	Ranking	1	2	6	8	3	10	3	5	7	9
Much worse	1										
Worse	2										
Same as	3										
Better	4										
Much better	5										
Reference	**3**										



In step two, all criteria were set as the same weighting factor to identify the importance of weighting. This result was also similar to the initial ranking, see Table 7 This sensitivity analysis shows that without the weighting the ranking is much more sensitive for changes in the matrix.

Table 7 Sensitivity Analysis 2

Concept scoring											
Criteria \ Concepts	Weight	A1	A2	B	C	D	E1	E2	F	G	H
Size	1,00	4	4	**3**	3	3	2	3	4	4	1
Sectioning of system	1,00	4	4	**3**	3	4	3	4	4	5	4
Speed	1,00	3	3	**3**	3	4	3	3	4	5	4
Strength	1,00	5	4	**3**	3	4	3	3	2	3	4
Complexity of prototype	1,00	3	3	**3**	3	3	2	2	2	2	2
Implement data capture	1,00	3	3	**3**	3	3	3	3	4	2	3
Lead time	1,00	3	3	**3**	3	3	2	2	2	2	5
Energy consumption	1,00	3	3	**3**	3	3	3	3	3	3	3
Complexity of interface	1,00	3	3	**3**	2	3	2	4	2	2	3
	Score	31	30	27	26	30	23	27	27	28	29
	Ranking	1	2	6	9	2	10	6	6	5	4
Much worse	1										
Worse	2										
Same as	3										
Better	4										
Much better	5										
Reference	**3**										



In step three, all weighting factors was translated into a linear numerical scale from 1-9 to compare with the other method mentioned in chapter 2.3.6. The result of this was showed the same ranking as the initial, see Table 8. Here the sensitivity lies in the higher weights which will influence the most.

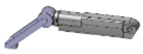
All together it can be argued that the sensitivity of the ranking is stable and that the results from the concept scoring is an adequate guideline for further development of those concepts. The weight matrix in Table 4 is a useful method for an adequate ranking.

Table 8 Sensitivity Analysis 3

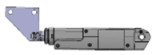
Concept scoring											
Criteria \ Concepts	Weight	A1	A2	B	C	D	E1	E2	F	G	H
Size	7,00	4	4	**3**	3	3	2	3	4	4	1
Sectioning of system	4,00	4	4	**3**	3	4	3	4	4	5	4
Speed	1,00	3	3	**3**	3	4	3	3	4	5	4
Strength	2,00	5	4	**3**	3	4	3	3	2	3	4
Complexity of prototype	5,00	3	3	**3**	3	3	2	2	2	2	2
Implement data capture	6,00	3	3	**3**	3	3	3	3	4	2	3
Lead time	9,00	3	3	**3**	3	3	2	2	2	2	5
Energy consumption	3,00	3	3	**3**	3	3	3	3	3	3	3
Complexity of interface	8,00	3	3	**3**	2	3	2	4	2	2	3
	Score	150	148	135	127	142	106	133	129	124	141
	Ranking	1	2	5	8	3	10	6	7	9	4

Much worse	1
Worse	2
Same as	3
Better	4
Much better	5
Reference	**3**

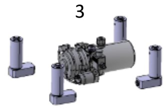
1



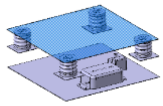
2



3



4



8 Conceptual Design

In this chapter, the development of the chosen concepts is described with suggested components.

8.1 Concept Electric Linear Actuator

The similarities of concept A1 and A2 in both ranking and technical solution led to a combination of those for further development. Both concepts had the advantage of high force relative to size and the attribute to divide the lift in different points. Previous mentioned LINAK AB was consulted during the implementation of the electric linear actuator.

8.1.1 System-Level Design

A lifting mechanism with electric linear actuators consists of one or multiple actuators which are controlled by a motor control unit. By using a four-point lift, stability when handling uneven weight distribution of cargo is acquired. Transmission of the force from the electric linear actuator can be obtained by mechanical gearing and the force and speed depends on the gearing ratio. The schematic illustration seen in Figure 18, illustrates the including components and how they are connected.

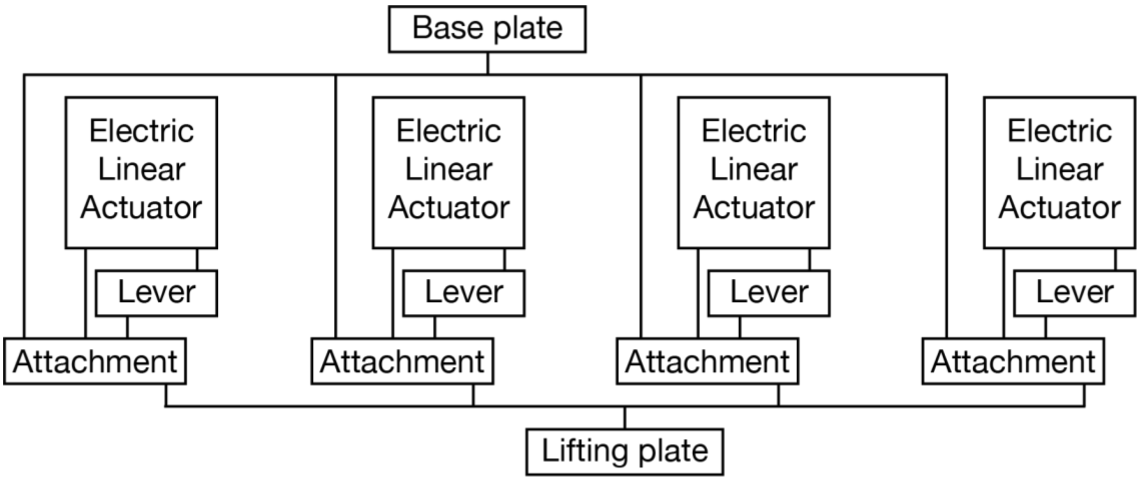


Figure 18 Schematic illustration of the Electric Linear Actuator system

Electric Linear Actuator

Further research and communication with LINAK AB resulted in new information regarding LA20. The speed of the electric linear actuator was stated as 10mm/s. The speed of 10mm/s was nominal speed for the lowest gearing configuration with a force of 600N. The highest gearing configuration which corresponds to the force of 2500N have a speed of merely 3 mm/s. The new information affects the concepts fulfillment of the Target Specification. If LA20 is used, both requirement of lifting speed and lifting weight cannot be met. As mentioned in chapter 6.1 there was no other suitable electric linear actuator with better performance than LA20. The argument that the selection criteria speed and strength, in the concept evaluation, was ranked as the two least important criteria led to a decision to further development of LA20. The LA20 can be designed with different gearing ratios to handle different lifting weights at different lifting times. The chosen configuration is shown in Table 9. Other configurations of LA20 could have been chosen with other lever dimensions for similar performances.

Table 9 LA20 specification

Specification	Value	Unit
Force	2500	[N]
Electric potential	24	[V]
Speed	3	[mm/s]
Dimensions (WxLxH)	36x248x46	[mm]

Lever

When designing the lever, an L profile was used which faced inwards towards the actuator, see Figure 19. Therefore, the total length of the lift mechanism does not exceed the length of LA20. The lever translates horizontal force into vertical.

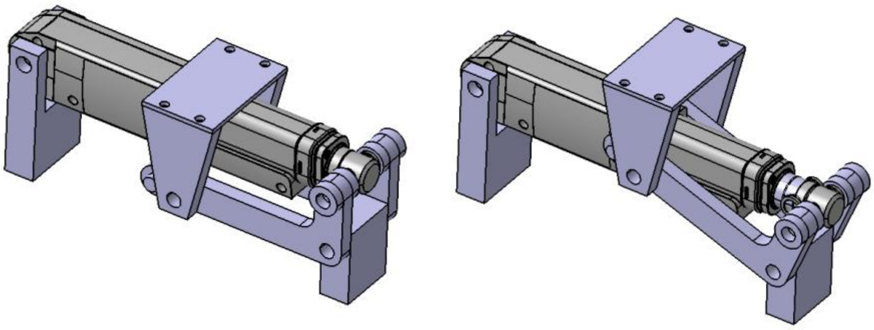


Figure 19 Illustration of a lift mechanism module with an electric linear actuator.

The lever dimensions were calculated with X1 set to 40 mm and X2 according to Equation 1, see Figure 21 for more information. A shorter lever is more favorable in a size perspective. Since it needs to be space between the actuator rod and the attachment joint the shortest length identified was X1 = 40mm. Due to the limitation of the electric linear actuator speed, a graph was made to visualize how the dimensions of the lever affect speed and lifting force, Figure 20. In the calculations, the lifting force is translated into the more comprehensible unit; weight the configuration is capable of lifting. This was done to identify an acceptable dimensioning of the lever that was favorable in both aspects. This resulted in a linear behavior and the center value was chosen to equally favor both aspects. This resulted in a lift mechanism that lifts a weight of 400kg with a lifting time of 4,5s and dimensions $X_1 = 40$, $X_2 = 101{,}8$, see Table 10 for concept performance.

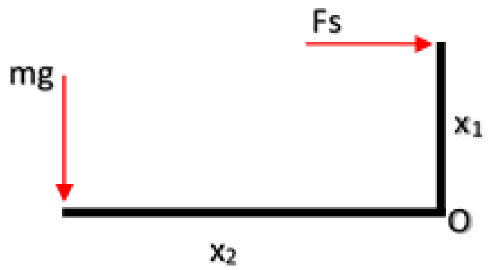


Table 10

Figure 21 Equlibrium illustration

Equation 1 (Fs=actuator force, m=mass, g=gravitational constant, x_i=lenght)

$$x_2 = x_1 * \frac{Fs}{mg}$$

Table 10 Data of concept performance.

Specification	Value	Unit
Actuator force **Fs**	2500	[N]
Lifting weight	400	[kg]
Qty. of actuators	4	[qty]
Vertical force **mg**	982	[N]
x1	40	[mm]
x2	101,8	[mm]
Actuator speed **v**	3	[mm/s]
Lifting time **t**	4,5	[s]

When the dimensions of the lever were set, a CAD-model was created and with it a FEM-calculation to verify the design. The maximal stress of the lever was simulated to 119MPa with a displacement of 0,23mm. If common construction steel is used with yield strength 235MPa the lever will be able to handle the lifting weight, see Figure 22.

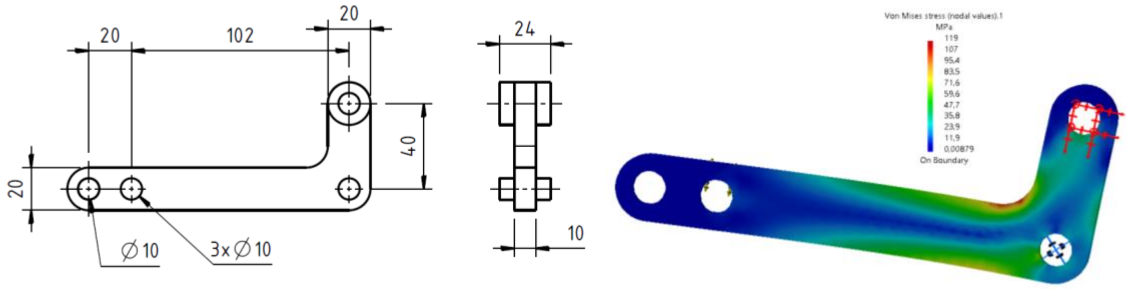


Figure 22 Dimensions and FEM-calculation of the lever

Attachments

Both the actuator and lever need to be connected to the base plate and lifting plate. Front and rear attachments were designed to handle the force of 2500N. Thus, dimensioning and FEM-calculation was executed. The attachment to the base plate was simulated to a maximal stress of 27MPa with a displacement of 0,05mm. Those would be stable with construction steel with yield strength 235MPa, see Figure 23.

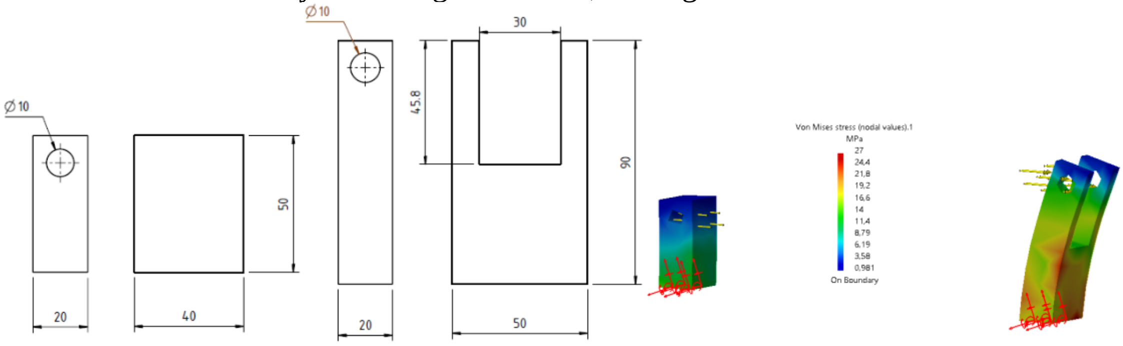


Figure 23 Dimensions and FEM-calculation of the front and rear attachments

The attachment to the lifting plate has a V-profile and acts like a distance between the lever and lifting plate. FEM-calculations confirmed the dimensions with a maximum stress of 3,88MPa with no displacement, see Figure 24.

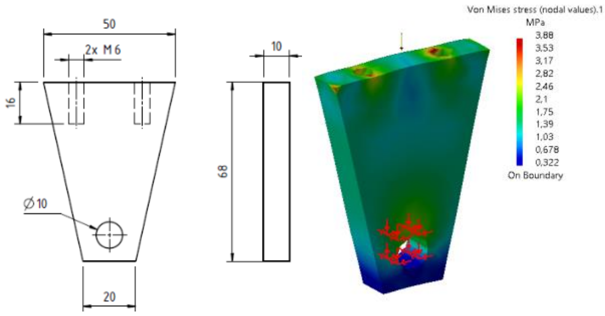


Figure 24 Dimensions and FEM-calculation of the V-profile

System Layout

The Electric Linear Actuator lifting mechanism is shown in Figure 25. Four modules with an actuator and a lever construction is mounted on a base plate. The actuators and levers are fixed at a base plate with attachments. The lever is connected to a lifting plate that acts as the contact surface against the object to be lifted. To design the whole system the four lift mechanisms must be placed to fit inside the specified volume 110x455x980mm. The layout in Figure 25 is a proposal of how the system can be designed to have free volume for other components in the ultra-compact AGV.

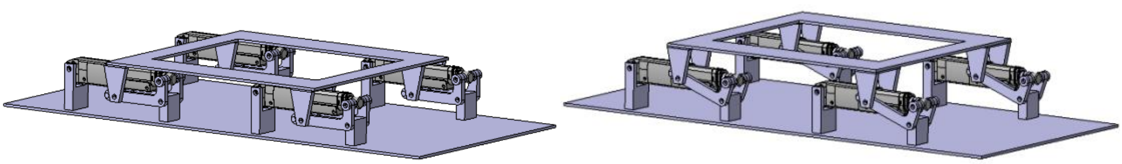


Figure 25 Illustration of Electric Linear Actuator lifting mechanism

A stroke of 14mm will generate a vertical lift of 35,7mm as seen in Figure 26. Since the levers rotate around a pivot joint, the mechanism will generate a horizontal movement of the top plate of around 6mm. All joints will be mounted with bushings to reduce friction.

The height 101mm is the total height of the module and depends on how high the front and rear attachments needs to be. In the implementation in an ultra-compact AGV these attachments can be integrated in the chassis and the actual height of the module can therefore be seen as the V-profile height of 68mm. An approximation of the lifting mechanisms box volume is then 4,8dm^3 for all four modules.

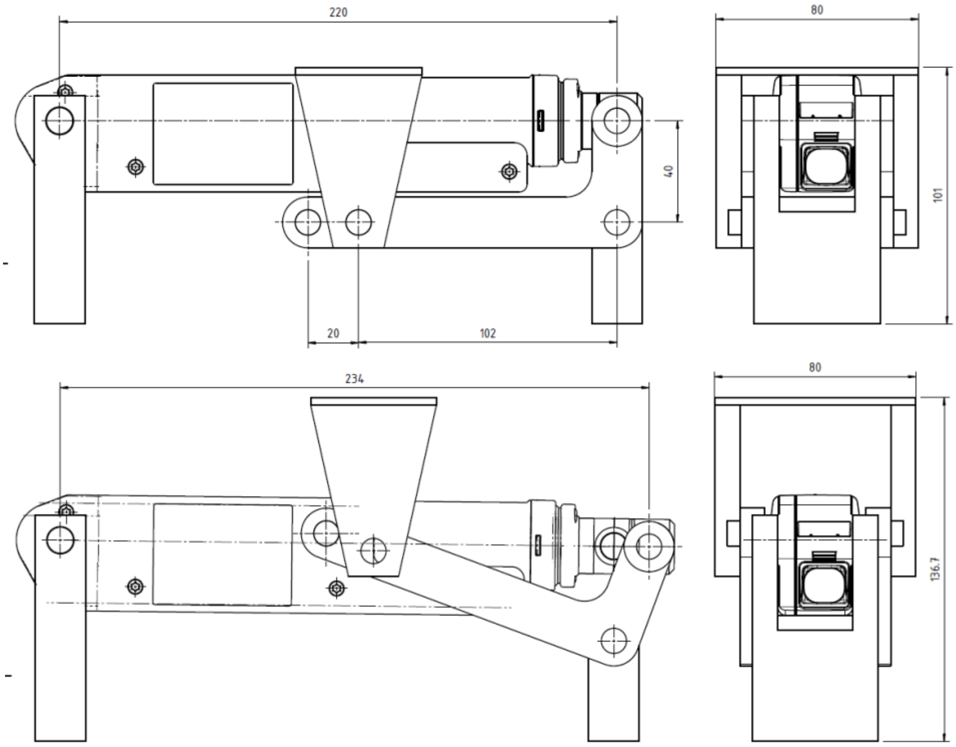


Figure 26 Illustration of Electric Linear Actuator lifting mechanism dimension

8.2 Concept Hydraulic System

Hydraulic systems are well known at Toyota Material Handling. The hydraulic design engineer Robin Bergström contributed with guidance and information about hydraulic systems. To find suitable components the Swedish hydraulic supplier Hydro Power Transmission AB (HPTAB) were pursued.

8.2.1 System-Level Design

The most challenging aspect when designing a suitable hydraulic system for an ultra-compact AGV is to meet the size requirements. Therefore, systems including one, two, three and four cylinders have been explored. There are no disadvantages in using an uneven amount from a hydraulic system perspective. But there are advantages as in less components are needed and with it less possibilities for leakage. However, from a material handling perspective four cylinders can handle uneven weight distribution of the cargo. Hydraulic cylinders are often created for a specific purpose and hydraulic system. The schematic illustration seen in Figure 27 illustrates the four-cylinder hydraulic system and how the components are connected. [16]

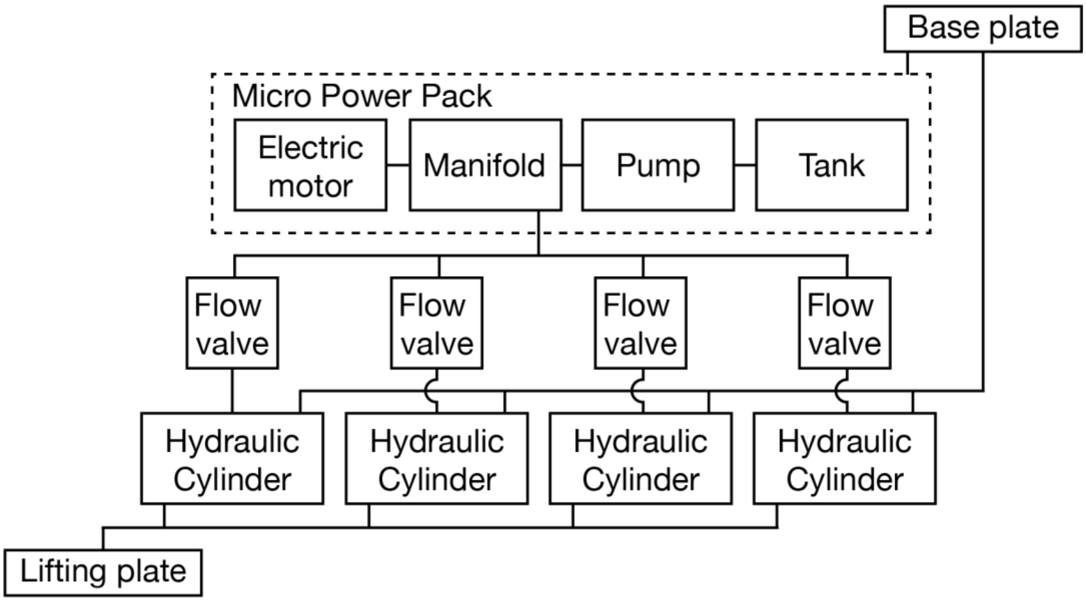


Figure 27 Schematic illustration of the Hydraulic System

Both single acting and double acting hydraulic systems were considered. A double acting system ensures equivalent lifting and lowering time and behavior but requires twice as much tubing and two ports from the Micro Power Pack, one from each side of the manifold. A double acting system also requires double acting hydraulic cylinders. A single acting system cannot ensure equivalent lifting and lowering time and behavior without using a spring to press the fluid out of the hydraulic cylinder. According to HPTAB, to include an internal spring inside the single acting hydraulic cylinder the lead time is significantly increased. However, an equivalent lifting and lowering time and behavior is not required. The concern affects lowering when the system is unloaded. When the hydraulic cylinders are loaded the gravity will press out the fluid. According to HPTAB the time is estimated to 2s. However, it must be tested in the specific application. The requirement of size determines that a single acting hydraulic system is desired. To avoid an increased lead time for the hydraulic cylinders an internal spring will not be included. If trouble with the lowering occur, then external springs can be added next to the hydraulic cylinders.

Hydraulic cylinders

The criteria for the Micro Power Pack is set by the hydraulic cylinders which dimensions are set by the pressure that is required to lift the desired weight. HPTAB supplies Micro Power Packs that produce a pressure up to 250bars. If only one hydraulic cylinder would be used in a system with a Micro Power Pack that produce a pressure of 250bar, the required piston diameter can be calculated with Equation 3 which originates from the simple pressure calculation seen in Equation 2. The result is that a theoretic single hydraulic cylinder with a piston diameter of 17mm and hydraulic pressure of 250bar can handle a static weight of 600kg. The total diameter of a hydraulic cylinder is according to hydraulic design engineer Robin Bergström approximately the piston diameter plus 10mm.

Equation 2 (D=diameter, m=mass, g=gravitational constant, p=pressure)

$$D = 2 * \sqrt{\frac{m * g / p}{\pi}}$$

Equation 3 (p=pressure, F=force, A=area)

$$p = \frac{F}{A}$$

This means that the piston diameter of a hydraulic cylinder pressurized to 250bar handling a static weight of 1200kg is required to be 24mm. The diameter difference is merely 7mm. However, the lifting weight and lifting time are interdependent from a hydraulic cylinder perspective. A larger piston diameter as well as adding more hydraulic cylinders requires more hydraulic fluid but less pressure.

The knowledge of that a small change in piston diameter results in the ability to handle a much greater weight led to the reasoning of applying a safety margin. In case of uneven weight distribution of cargo each lifting point may not be equally loaded. A safety factor of two was considered reasonable which implies that each hydraulic cylinder is required to handle 300kg. The new requirement correlates to the event that the entire weight to be lifted is placed on one side of the ultra-compact AGV. The horizontal force which might stress the lifting mechanism while the ultra-compact AGV is driving is estimated to 1250N.

The lifting weight and horizontal forces were presented to HPTAB and suitable hydraulic cylinders were designed. The previously used calculation is only for a static case and for one hydraulic cylinder. For the real hydraulic cylinders, a dynamic factor as well as a safety margin must be applied to ensure that the requirements are met. The hydraulic cylinder specification is seen in Table 11.

Table 11 Hydraulic cylinder specification

Specification	Value	Unit
Height	110	[mm]
Stroke length	38	[mm]
Piston diameter	20	[mm]
Cylinder diameter	42	[mm]
Max lifting weight (per cylinder)	300	[kg]
Max horizontal force (per cylinder)	1250	[N]

With four hydraulic cylinders with a piston diameter of 20mm and the static weight of 1200kg, a theoretic pressure of 94bar is required, according to Equation 3. The required pressure must be considered when choosing a Micro Power Pack.

Micro Power Pack

The biggest component in the hydraulic system is the Micro Power Pack, see Figure 28. The limiting dimension of the Micro Power Pack is height and is a consequence of the manifold which connects the electric motor to the pump and oil tank as well as distributes the oil to ports. The ports are distributed on both sides and on the top of the manifold. According to HPTAB the side ports are often used for different valves and filters whereas the top ports are used as outlet and inlet. The height of the manifold is 100mm and therefore, only the side ports will be used in the ultra-compact AGV application.

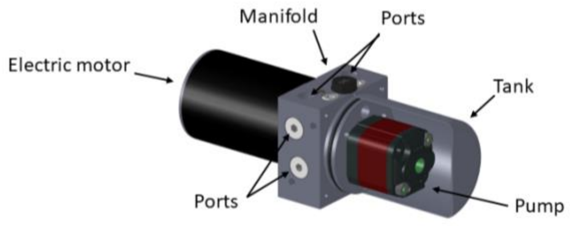


Figure 28 A Micro Power Pack [17]

The length of the Micro Power Pack is principally set by the length of the electric motor and oil tank. The lifting time depends on the flow of fluid the electric motor and pump can produce as well as the volume inside the hydraulic cylinders which needs to be filled. The Micro Power Pack must be able to produce a hydraulic pressure above 94bar to ensure a safe lifting of 1200kg. In addition to the pressure requirement is the requirement that the system must lift 600kg in two seconds. Suitable components have been chosen and configured in cooperation with HPTAB, see Table 12 for Micro Power Pack specification.

Table 12 Micro Power Pack specification

Specification	Value	Unit
Dimensions (WxLxH)	110x286x110	[mm]
Power	800	[W]
Pump volume	1,5	[cm^3]
Tank volume	0,4	[dm^3]

Flow valve

According to hydraulic design engineer Robin Bergström, flow divider combiners are used in hydraulic systems with multiple hydraulic cylinders to achieve a simultaneously elevated system. However, the flow divider combiner requires a minimum flow of fluid which is not obtained in the hydraulic system previously introduced. A solution to reduce instability is to include one-way flow valves to each hydraulic cylinder. The flow valve will even out the pressure in the system and make it more stable. As a result of using a single acting hydraulic system only flow valves controlling the flow when lifting can be implemented. Using a flow valve for lowering would increase the previous concern regarding the fluid leaving the hydraulic cylinder when lowering.

System Layout

The layout of concept Hydraulic System in the ultra-compact AGV is seen in Figure 29. The hydraulic cylinders should be distributed symmetrically for stability. The tubes and wires can be routed adjacent to other components in the ultra-compact AGV and will therefore not consume much volume. Tubes, wires and fittings are not included in the visualization. The Flow valves are seen in red. An approximation of the lifting mechanisms box volume excluding top plate, tubes and wires is 4,6dm^3.

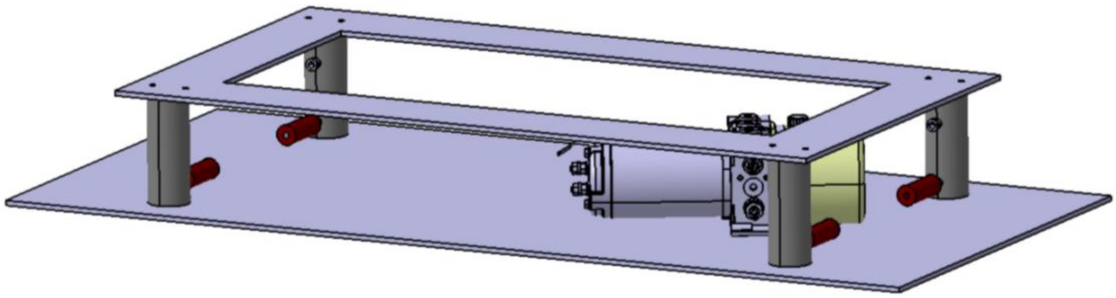


Figure 29 The layout of concept Hydraulic System

8.3 Concept Air Suspension

The concept Air Suspension was considered interesting because it is, by TMHMS, a possible but unknown technology. Pneumatic systems are used in other applications that can be related to the context of an ultra-compact AGV such as the car-industry and manufacturing-industry. The motion and fluid control company IMI Precision Engineering, IMI PE, were pursued for components and pneumatic system information.

8.3.1 System-Level Design

Compressed air can be created by a compressor or released from a pressurized container. The system can consist of a single stronger or several weaker air bellows. If a single air bellow is used, less tubing and valves are needed which reduces the possibility of leakage. By using several air bellows each component can be smaller and the system will handle uneven weight distribution better. Several lifting positions are preferred for stability; hence four air bellows are chosen. A manifold forward the airflow from the compressor to the air bellows when lifting and releases the air from the air bellows when lowering, thus both the manifold and compressor must be controllable. Tubing and fittings between the air bellows, manifold and compressor are required. The schematic illustration seen in Figure 30 illustrates the air suspension system and how the components are connected.

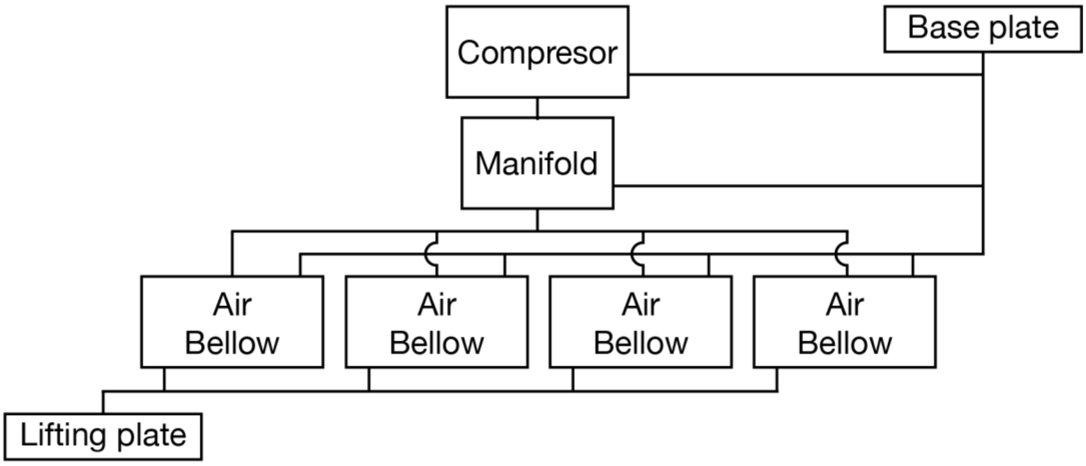


Figure 30 Schematic illustration of the Air Suspension system

A start-lift signal will activate the compressor and pressurize the air which passes through a check valve in the manifold. A stop-lift signal will deactivate the compressor and the check valve makes sure that the pressure is held in the air bellows. A start-lower signal will open an exhaust valve in the manifold to release the pressurized air and a stop-lower signal will close the exhaust valve. One signal for when the lift mechanism is in a lowered state and another for when the lift mechanism is in an extended state is required for automation. This will be achieved by using limit switches or by analyzing the flow of current over the compressor.

Air bellows

To simplify positioning of the air bellows inside the ultra-compact AGV a compact diameter is preferred. The vertical height cannot exceed the restriction of 110mm, when deflated, which must be considered when choosing air bellow height, port fitting and connecting interface. The port is located on one of the ends and the hole pattern for installation is located on both opposing edges, see Figure 31.

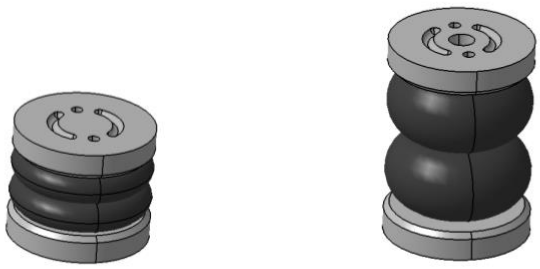


Figure 31 Retracted air bellow with port side down and extended with port side up.

A compact air bellow from IMI PE called PM/31022 was identified which exceeds the requirements from the Target Specifications, see Table 13. However, it is uncertain how well the air bellows handle horizontal forces. If the air bellows are collapsed or extended more than specified, they might take damage. Therefore, the air bellows require a mechanical stop at both retraction and extension.

Table 13 Air bellow PM/31022 specification

Specification	Value	Unit
Max Pressure	8	[bar]
Installation height	65	[mm]
Stroke Length	45	[mm]
Diameter	80	[mm]
Area	0,005	[m^2]
Extended volume	0,000375	[m^3]
Theoretical force (per cylinder)	2130	[N]

According to Equation 4, a pressure of 2,946bar is required to lift the weight of 150kg (1473N), 600kg (5892N) divided by four bellows, with an area of 0,005m^2.

Equation 4 (p=pressure, F=force, A=area)

$$p = \frac{F}{A}$$

The extended volume of the air bellow is approximated to a cylinder with sectioning area of 0,005m^2 and height 0,075m. The height is the extended height of 110mm minus the flanges thickness of 35mm. Therefore, the extended volume is calculated to 0,000375m^3. The total extended volume of the system is then 0,0015m^3.

Compressor and manifold

A compressor kit from Air Lift, including the smallest compressor encountered within reasonable specifications, was identified by internet-based research. This compressor kit is designed for private costumers to install an air suspension system in their car by themselves. The suppliers state that the compressor kit can handle the weight of large cars such as pick-up trucks. The kit includes compressor, manifold, remote-control, wiring, fittings, cables, tubing and other required hardware. Everything except air bellows. The compressor kit includes a Bluetooth controller to select the pressure is the system. Three programmable settings are available as well as adjustment of 1 psi per click. The compressor kit is designed to be used in a system with two air bellows. No information exists on how it would handle four air bellows. In an ultra-compact AGV the associated remote control would not be used because it restricts the ability of automatization. However, the wireless control feature is considered useful in the event of building a test-rig prototype.

Table 14 Air Lift Compressor kit specification

Specification	Value	Unit
Pressure	8,3	[bar]
Electric potential	12	[V]
Current	12	[A]
Power **P**	144	[W]

Compressor dimensions (WxLxH)	140x173x93	[mm]
Manifold dimensions (WxLxH)	70x70x62	[mm]

The max power of the compressor is 144W and according to Equation 5, the airflow available at pressure p=2,946bar is Q = 0,000489m^3/s.

Equation 5 (Q=flow, P=power, p=pressure)

$$Q = \frac{P}{p}$$

The fastest theoretic lifting time when lifting 600kg is calculated to t=3,1s, according to Equation 6. The new information affects the concepts fulfillment of the Target Specification. Since a lighter lifting weight requires a lower pressure the flow is increased and lifting time shortened. Therefore, a graph was made to visualize how the lifting time was affected by lifting weight, see Figure 32. These calculations are based on the max power of 144W and displays the theoretical lifting time and lifting weight. The calculations are done with system losses excluded. This resulted in a linear behavior that either fulfilled the requirement of lifting time or lifting weight. Since the selection criteria speed and strength, in the concept evaluation, was ranked as the two least important criteria the center value was chosen to favor both aspects equally. Therefore, the lifting time for lifting 500kg is 2,6s.

Equation 6 (t=time, V=volume, Q=flow)

$$t = \frac{V}{Q}$$

The lowering time is foremost determined by the venting capacity in the exhaust valve inside the manifold. Unfortunately, no information of the exhaust valve is available. To determine lowering time two aspects were considered. Firstly, the air passes through the same tubes as when inflated which might limit the flow. Secondly, the weight to be lifted counteracts the air flow when lifting and assists in pushing the air out when lowering. Therefore, the lowering time is thought to be less or equivalent to the lifting time.

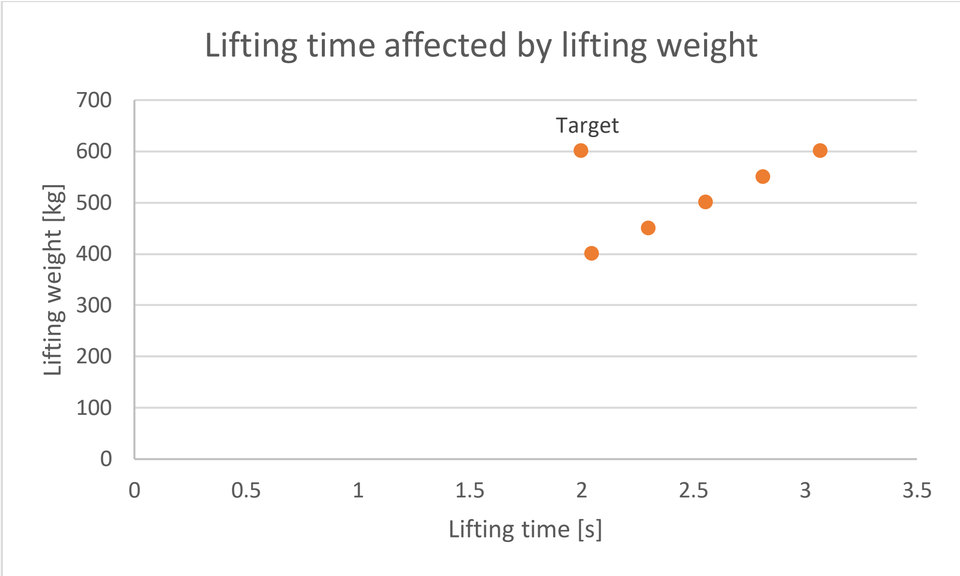


Figure 32 Graph of how the lifting time is affected by lifting weight.

System layout

The layout of concept Air suspension in the ultra-compact AGV is seen in Figure 33. To create a complete pneumatic system including the compressor kit and air bellows fittings and tubes are required. The tubes and cables can be routed adjacent to other components in the ultra-compact AGV and will therefore not consume much volume. Tubes, wires and fittings are not included in the visualization. A sheet metal component will create the possibility to mount the tubing to the port beneath the air bellows. An approximation of the lifting mechanisms box volume excluding top plate, wires, tubing and fittings is 4,22dm^3.

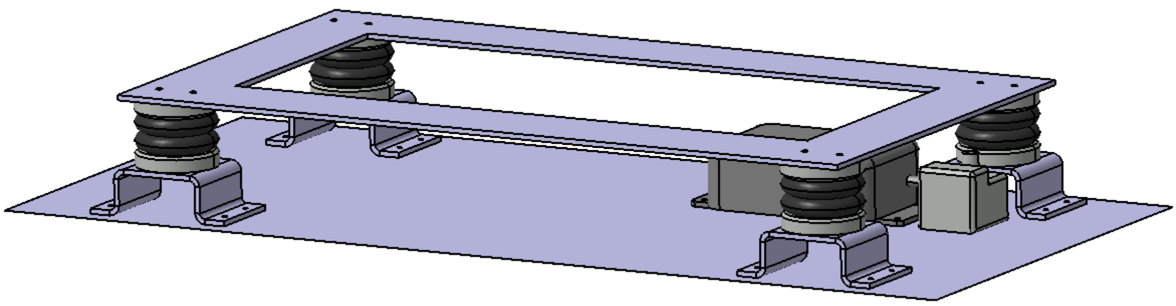


Figure 33 The layout of concept Air suspension

9 Verification

To assess the suitability of the three concepts they were compared against the Target Specification. The specification force density is introduced, which is the force of the lifting mechanism divided by the box volume it occupies. The force density offers an insight to how well the concept would perform in other applications. The comparison is seen in Table 15.

Table 15 Target Specification combined with specifications of the concepts.

ID	Description	Marginal value	Electric linear actuator	Hydraulic system	Air suspension	Unit
1	Lifting height	**35**	35,7	38	45	[mm]
2	Lifting time	**2**	4,5	2	2,6	[s]
3	Lowering time	**2**	4,5	2	2,6	[s]
4	Lifting weight	**600**	400	600	500	[kg]
5	Height	**110**	68	110	93	[mm]
6	Volume of lifting mechanism	**9**	4,8	4,6	4,22	[dm^3]
7	Largest coherent box volume	**4,9**	1,2	3,5	2,25	[dm^3]
	Force density	**-**	818,3	2561,7	1396,2	[N/dm^3]

9.1 Concept Electric Linear Actuator

As explained in chapter 8.1 lifting height, lifting and lowering time and lifting weight are interdependent and adjustable by the dimensions of the lever. These parameters can be varied within a limited range. The calculations are considered sufficient and the system should behave as designed. Friction has consciously not been added in the calculations with the motivation that the affected joints will be equipped with bushings which reduce the influence of friction.

The electric linear actuator concept does not fulfill the criteria of lifting time, lowering time or lifting weight. However, as explained in chapter 8.1, it was considered interesting to keep developing the concept as it would be a favorable solution in applications with lower requirements of lifting weight, lifting time and lowering time. A positive attribute is that the electric linear actuator concept has the smallest coherent boxed volume. Electric linear actuators are considered a promising technical principle, but the technology has not yet reached the speed and force required for the ultra-compact AGV.

9.2 Concept Hydraulic System

The hydraulic system is considered the most powerful lift mechanism with the capability to lift a weight of 1200kg and is the only concept which can lift the weight of 600kg in two seconds. TMHMS are experienced in the field of hydraulics which should benefit in taking the hydraulic system to the market. However, the electric hydraulic system described in this concept to use as a lifting mechanism qualifies as the smallest TMHMS have ever handled. No modifications to make the hydraulic system smaller has been identified, but there are other components or configurations that could be applied if more lifting weight or longer stroke is desired, at the cost of size.

The lowering time is as explained in chapter 8.2.1 tainted with the concern that when unloaded the gravitation will not be enough to lower the lifting plate within the time limit. However, this potential problem has a simple solution. External springs can be inserted to pull the lifting plate down and press the fluid out.

9.3 Concept Air Suspension

The air suspension concept does not fulfill the criteria of lifting time, lowering time or lifting weight. The limiting component in the system is the compressor which does not produce enough flow to meet the requirements set by the air bellows. No alternative compressor that also met the height requirement of 110mm was identified. The pressure the air bellow requires to lift said weight also impacts the lifting and lowering times. Higher pressure equals more air, thus longer time to inflate or deflate. Therefore, a more powerful compressor or smaller air bellows would make an air suspension system that does meet the requirements.

The use of an air system as a lift mechanism is considered an interesting alternative to the established hydraulic system. Even though the identified components for the air system does not meet the Target Specification, the system has both advantages and disadvantages. The concept air suspension has the smallest system box volume. With air as the working fluid, no tank is needed, nor does leaked or released air contaminate. A negative aspect is that an air compressor creates more noise than a liquid pump.

10 Results

The three following concepts have been developed to meet the requirements for an ultra-compact AGV. However, the concepts Electric Linear Actuator and Air Suspension does not fulfill the Target Specification in terms of lifting weight and lifting time. To fulfill the target specification with these concepts, the technology needs to advance. No other suitable electric linear actuator has been identified in terms of size and sectioning of system. The compressor for the Air Suspension is the smallest identified and more powerful alternatives exceed the height limit of 110mm.

It has been identified that TMHMS finds interest in new and other solutions than hydraulic systems. Therefore, these concepts will demonstrate a possible implementation and act as a knowledgebase for future projects. In general, the concepts can be implemented in a large variation of products where the requirements of lifting weight and lifting time is less demanding.

All concepts have a four-point lift mechanism for stability and to better handle uneven weight distribution. All concepts have the advantage of sectioning of the system, which means that the system consists of several separable sections rather than one big piece. The placement of these sections is flexible and adaptable to modifications of the distribution of sub-systems inside the ultra-compact AGV.

10.1 Concept Electric Linear Actuator

The Electric Linear Actuator concept is a system with four modules that work simultaneously to generate a lift, see Figure 34. The modules consist of attachments, lever and actuator. Each module delivers a vertical force of 982N. A lift of 35,7mm takes 4,5s. See Table 16 for component list and Table 17 for concept specifications.

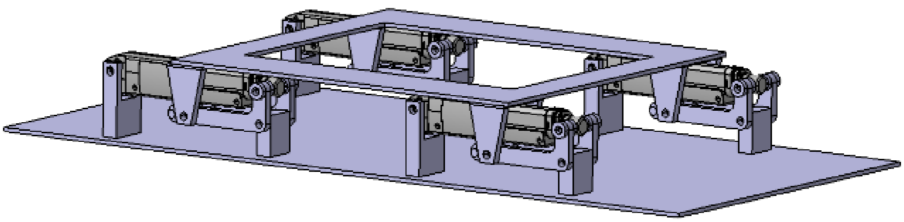


Figure 34 Visualization of concept Electric Linear Actuator

Table 16 Concept Electric Linear Actuator component list

Components	QTY.	Company
Electric linear actuator LA20	4	LINAK AB
Rear attachment	4	TMHMS
Front attachment	4	TMHMS
V-profile attachment	8	TMHMS
Lever	8	TMHMS

Table 17 Concept Electric Linear Actuator specification

Description	Value	Unit
Lifting height	35,7	[mm]
Lifting time	4,5	[s]
Lowering time	4,5	[s]
Lifting weight	400	[kg]
Height	68	[mm]
Volume of lifting mechanism	4,8	[dm^3]
Largest coherent box volume	1,2	[dm^3]
Force density	818,3	[N/ dm^3]

10.2 Concept Hydraulic System

The hydraulic system concept consists of a Micro Power Pack that is connected to four hydraulic cylinders via flow valves, see Figure 35. The flow valves regulate the flow for a simultaneous lift. Each hydraulic cylinder can generate a vertical force of 2946N. A lift of 38mm will be managed in 2s. See Table 18 for component list and Table 19 for concept specifications.

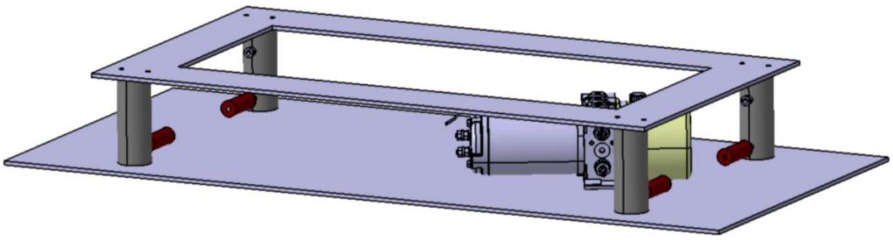


Figure 35 Visualization of concept Hydraulic System

Table 18 Concept Hydraulic System component list

Components	QTY.	Company
Powerpack	1	HPTAB
Flow valve	4	HPTAB
Cylinder	4	HPTAB
Tubes	2m	TMHMS
T-couplings	3	TMHMS

Table 19 Concept Hydraulic System specification

Description	Value	Unit
Lifting height	38	[mm]
Lifting time	2	[s]
Lowering time	2	[s]
Lifting weight	1200	[kg]

Height	110	[mm]
Volume of lifting mechanism	4,6	[dm^3]
Largest coherent box volume	3,5	[dm^3]
Force density	2561,7	[N/ dm^3]

10.3 Concept Air Suspension

The air suspension concept consists of a compressor that generates airflow via a manifold to four air bellows, see Figure 36. The air bellows can be placed in desired position in an ultra-compact AGV but is restricted to be placed symmetrical around the center of gravity to generate a simultaneous lift. When the compressor generates a pressure of 2,9bar, each air bellow produces a vertical force of 1227N and lifts 45mm in 2,6s. See Table 20 for component list and Table 21 for concept specifications.

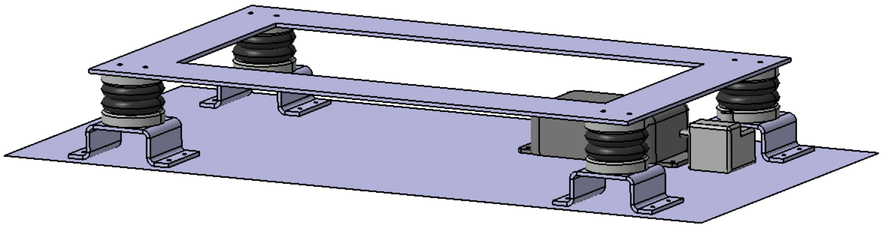


Figure 36 Visualization of concept Air Suspension

Table 20 Concept Air Suspension component list

Components	QTY.	Company
Compressor	1	AirLift
Manifold	1	AirLift
Air bellows	4	IMI precision
Air Bellow mount	4	TMHMS
Tubes	2m	IMI precision
Air bellow fittings	4	IMI precision
T-couplings	3	IMI precision
Inch to mm converter	1	IMI precision

Table 21 Concept Air Suspension specification

Description	Value	Unit
Lifting height	45	[mm]
Lifting time	2,6	[s]
Lowering time	2,6	[s]
Lifting weight	500	[kg]
Height	93	[mm]
Volume of lifting mechanism	4,22	[dm^3]
Largest coherent box volume	2,25	[dm^3]
Force density	1396,2	[N/ dm^3]

11 Discussion

11.1 Method discussion

11.1.1 Workshops

Interesting and rewarding insights were obtained by holding a test-workshop. The participators experienced the activities and arrangement with an outsider's perspective. Discussions of how instructions were perceived led to adjustments so that they would be interpreted as desired. As described in chapter 2.3.4, timing and logistics are essential for a successful session. By doing the test-workshop the estimation was evaluated. Information of which activities that required more facilitator involvement as in encouragement, guidance or restrictions arose. This worked as preparation for the following actual workshops. By first doing the test-workshop novice mistakes were reduced.

The workshops were carefully planned and well executed. The set of activities engaged the participants. Three activities during 90 minutes with five to six participators is considered an appropriate setup. The time went by fast, but each participator was given the opportunity to express every thought and idea. In a playful manner the warm-up exercise succeeded in encouraging the participators to be creative and open-minded. The activity was performed with laughter and smiles. It had a good balance of challenging rules to a known child's play. The brainstorm's foremost purpose was to get the participators focused about handling objects vertically. Without following questions or tasks it was hard to know if the participators were pointed in the right direction or not. However, the level of partaking was used as an indication of involvement. The brainwriting and brain drawing activity was intended to collect the participators ideas, thoughts and knowledge. It seemed as if a blank paper was considered uncomfortable for some participators as they had a hard time getting started whereas other participators started right away. This was a predicted concern and a creative atmosphere and a selection of different colors, drawing utilities and printed pictures were supposed to counteract the phenomena. It could be a personality issue and, in that case, difficult to affect. It could be that the creative atmosphere was not as distinct as desired or that the participators did not have enough time to reach their creative state. Perhaps a preparatory task could increase the creativity. Different colors, drawing utilities and printed pictures were by most participators unused, thus not considered a necessity.

A rewarding, unintended, effect of the workshop was the network which was established with the TMHMS co-workers. It was seen both as a social pleasure and as a valuable source of knowledge throughout the project. With a name and associated face, it was considered easy to start spontaneous conversations and ask related questions.

11.1.2 Categorization

A categorization was executed to acquire an overview of the ideas and concepts generated during the workshops. The ideas and concepts were sorted by technical principle and function means into a function means flow chart. The activity was inspired by the

Function Means Tree found in the Functional Specification method. The function means flow chart was considered an uncomplicated and time efficient activity. The result is considered a comprehensible visualization that simplifies the involvement of stakeholders.

11.1.3 Follow-up meeting

The amount of ideas and concepts was considered overwhelming and no suitable method for an initial selection was found that could be fulfilled within the available period of time, thus the follow-up meeting was formed. The follow-up meeting was arranged to receive more knowledge about the generated technical principles and function means. A digital survey was created to quantify the participators opinions and knowledge. The follow-up meeting was a successful activity to maintain the involvement of the workshop participators and receive an initial selection. The questions in the survey was created to be quick and easy. A digital survey simplified the compiling of result which then was visualized in spider charts. Spider charts was considered practical when handling several measures.

11.1.4 Concept development

The most difficult aspect of the concept development phase was to simultaneously and equally develop around 10 concepts. Some concepts, such as most of the electric linear actuator concepts were mostly affected by custom designed components and required calculations and detail design. Other concepts, such as the vertical ball screw or air suspension were more component dependent, and the performance was limited by the specification of identified products. The concepts required different means of development which consumed a various amount of time. The three predefined areas could be applied for all concepts and was used to measure how far each concept was developed.

11.1.5 Concept Evaluation/Selection

The selection criteria weighting matrix was a productive way to weight the criteria relative each other. This entailed that all criteria were compared equivalent. The importance of weighting was proven by the sensitivity analysis in Table 7. It proved that without weights the ranking resulted in similar values and that concept variations gave significant changes of the ranking. It can then be difficult to argue which concept that is favorable.

The selection criteria list was a combination of the Target Specification, business feasibility aspects and criteria from TMHMS supervisors. The business feasibility aspects were useful to broaden the selection criteria list. In further development those aspects will be more important but since a proof-of-concept prototype only verifies the function some of the aspects was not necessary in this project.

The technical criteria from the selection criteria list could have been separated from other project criteria such as lead time and complexity of prototype. This to objectively rank the best concept from a technical perspective and then rank each concept against the project restrictions. This gives a further understanding of what technical solution that is best and then which concept that is most favorable for the project.

When evaluating the concepts, the Concept Screening and Scoring method was used. The concept scoring part was implemented since the level of detail in the concepts was considered well described. Concept scoring combined with the weighted criteria resulted in an adequate concept ranking where the highest ranked concept was chosen. The sensitivity analysis that was implemented helped verify the ranking and proved its reliability. More iterations could have been done in the analysis, such as changing the reference concept.

11.1.6 Conceptual design

In the conceptual design phase, suppliers and manufacturers were contacted to gain more knowledge of technical principles, systems and available components. The contacts were important in this project as they possessed extensive knowledge of their products and associated systems. The contacts were introduced to the case and helped in choosing components and configurations that met our requirements. If the required components did not exist, the contacts assisted in understanding what modifications had to be done to function in an ultra-compact AGV. This was a productive way to further develop the concepts to be closer to realization and to initiate contact for quotation. In these kinds of technical concepts where suppliers are specialists in their products a lot of knowledge can be gathered when including them in the development phase. The supplier then get insight in future product demands and the technology might advance.

12 Conclusion

The thesis follows one perception of a product development process. The product development project was executed in close collaboration with supervisors at Toyota Material Handling and together with selected employees at the site. The project was severely affected by the limited timeframe as a consequence of the proof-of-concept deadline. If other individuals would have been involved or other prerequisites been present, the project and the result might have turned out differently. One of the presented concepts fulfill the Target Specification for an ultra-compact AGV. However, all concepts presented is to be seen as guidance in developing compact lifting mechanism for various purposes in autonomous material handling.

12.1 Answer Question 1

What concept of a lifting mechanism is potentially best suited for an ultra-compact AGV?

The concept Hydraulic System is considered the best suited lifting mechanism for an ultra-compact AGV. This system distinguishes itself in two aspects. The first is that the target specification is fulfilled with the lifting weight exceeding the requirements with a factor two. This implicates that this system can be used in even more demanding applications where heavier load is desired. The identified system is considered difficult to make smaller. However, up-scaling is possible and will lead to a system with better performance.

The second aspect is that TMHMS have considerable knowledge of hydraulic systems. The advantage is that in-house experience will ease de further development and implementation of such a solution in their projects. Well established contacts with suppliers and manufacturers reduces the lead-time of hydraulic components which is seen favorable when the proof-of-concept prototype is due to the spring of 2019.

12.2 Answer Question 2

From a general perspective, which factors are affecting the development of a product where space is restricted?

Determining components in time, Interface between interacting components or subsystems, Proximity of non-interacting components or subsystems and Sectioning of system were considered the most critical aspects when developing a product were space is restricted.

Determining components in time
In the beginning of a product development project the potential of change is greatest but the knowledge about the product is limited. As the knowledge of the product grows the possibility for change is reduced. Several components and subsystems are interdependent which means that if a component is exchanged then possibly other changes are required too. In the beginning of the development process the available knowledge might not be

considered enough to make justified component decisions. A circular phenomenon occurs as component selection becomes harder because no components have been selected. To avoid this phenomenon the limiting component or subsystem must be determined. The limiting aspects of a component or subsystem can be a consequence of environmental regulations, safety regulations, knowledge or experience.

Interface between interacting components or subsystems
Several components or subsystems are connected to share information, energy or mechanical movement. These interfaces should be investigated and defined early in the process. When the interfaces are defined, related components and subsystems can be grouped together to reduce the risk of missing connections which results in system failure. Grouping interacting components also simplifies troubleshooting and serviceability. A predefined interface between two unknown components can simplify the development of each component and allows for a parallel workflow.

Proximity of non-interacting components or subsystems
A selection of non-interacting components or subsystems have requirements of their surroundings. For example, heat sensitive components should not be placed close to components that generate heat. Other occurring examples are components that produce magnetic fields or components that are sensitive to liquid or dust. This problem can be reduced by thoughtful component distribution or by creating protective shields between concerned components.

Sectioning of system
Sectioning of system means that the system consists of several separable sections rather than one coherent piece. Components are rarely cubical which often results in that portions of the space in the proximity of a component becomes unusable. Bigger components often lead to more unusable space. Smaller sections of a system grant a more flexible and adaptable distribution of components.

12.3 Answer Question 3

How can in-house knowledge contribute to the development of a technical solution?

A Design Workshop is considered a successful activity to acquire and utilize in-house knowledge to improve the development of a technical solution. During the workshop, the participants were incorporated into the project. Ideas and solutions for lifting mechanisms were generated and evolved. As the participants contributed with their ideas and experience they established a belonging to the project and an incentive to see a successful result. This led to accommodating collaborations with employees that lasted throughout the project.

13 Future development

The concept hydraulic system is presented with a component list which was produced in cooperation with the supplier HPTAB and the hydraulic design engineer Robin Bergström. To further evaluate this concept the components must be purchased, and the system tested. The uncertainty of this concept is as previously stated regarding the lowering time. By performing tests on the system, information will be acquired if the system needs lowering support. If the need does exist a study should be executed to examine if external springs, hydraulic cylinders with internal springs or a double acting hydraulic system should be used in the fully functioning mass-producible ultra-compact AGV.

When the hydraulic system has been delivered to TMHMS the system could either be assembled as a test-rig prototype or directly inserted in the proof-of-concept prototype. Regardless, attachments for the hydraulic cylinders as well as placing of suitable tubes and fittings must be designed to complete the system. To lift objects, a lifting plate must be designed with interface against the four cylinders.

When the system is assembled the tests may begin. To acquire information about lifting and lowering performance, several lifting cycles should be executed with varying weights. A lifting cycle involves a lifting, a short rest at the top and then a lowering. The tests should start with no load and then gradually increase the weight to 600kg. The lifting time and lowering time is recorded for each cycle. This test should generate information whether the lowering requires assistance to meet the requirements of lowering time. If the system does not operate as intended, the previous tests should give a clue of how much force external springs would need to add. Suitable springs must be identified and connecting interface towards the bottom plate and lifting plate must be designed. The previous test should be repeated to ensure the performance of inserted springs.

If the system now operates as intended the lifting mechanism for the proof-of-concept prototype it is considered successfully completed. The proof-of-concept prototype can now be used to determine if the concept should be further developed into a fully functioning mass-producible product. If that is the case, the next step is to investigate if no spring, external spring, internal spring or double acting hydraulic system should be used in a mass-producible product. If changes of the lift mechanism occur than the initial test should be repeated. When the lifting mechanism is considered successfully completed a test-engineer should be involved to perform life-time and durability tests on the lift mechanism. Modifications and optimization of the system may be required.

14 References

[1] "Toyota Material handling," 2017. [Online]. Available: https://toyota-forklifts.eu/our-offer/. [Accessed 24 08 2018].

[2] "Toyota Material Handling," 2017. [Online]. Available: https://toyota-forklifts.co.uk/trucks-and-services/products/automated-trucks/. [Accessed 24 08 2018].

[3] Q. Li, A. C. Adriaansen, J. T. Udding and A. Y. Pogromsky, "Survey of Research in tha Design and Control of Automated Guided," no. European Journal of Operational Research. 170(3):677-709., 2006.

[4] L. Schulze, S. Behling and S. Buhrs, "Automated Guided Vehicle Systems:," vol. 2, 2008.

[5] E. A. Parr, Hydraulics and pneumatics. A technician's and engineer's guide, Amsterdam ; Boston : Elsevier ; Kidlington, Oxford, U.K. ; Burlington, Mass: Butterworth-Heinemann, 2011.

[6] C. Gonzalez, "What's the Difference between Pneumatic, Hydraulic, and Electrical Actuators?," *Machine Design,* 2015.

[7] "Engineering 360," IEEE, [Online]. Available: https://www.globalspec.com/learnmore/mechanical_components/springs/air_springs. [Accessed 20 08 2018].

[8] "LINAK," [Online]. Available: http://www.linak.se/om/?id3=5003.

[9] C. Gonzalez, "Machine Design," 14 03 2018. [Online]. Available: https://www.machinedesign.com/motion-control/new-memory-metal-allows-wings-take-shape-flight. [Accessed 22 08 2018].

[10] "Saesgetters," Saes group, 11 04 2018. [Online]. Available: https://www.saesgetters.com/products-functions/products/shape-memory-alloys/shape-memory-alloys-actuators. [Accessed 22 08 2018].

[11] The Editors of Encyclopaedia Britannica, "ENCYCLOPÆDIA BRITANNICA," [Online]. Available: https://www.britannica.com/science/electromagnet. [Accessed 12 11 2018].

[12] K. T. Ulrich and S. D. Eppinger, Product Design and Development, New York: McGraw-Hill Education, 2012.

[13] A. van Boeijen, J. Daalhuizen, J. Zijlstra and R. van der Schoor, Delft Design Guide, Amsterdam: BIS Publishers, 2016.

[14] B. Martin, Univeral Methods of Design, Beverly, Mass. : Rockport Publishers, 2012.

[15] R. V. E. A. V. F. a. E. V.-J. Daniel Justel, "Evaluation method for selecting innovative product concepts with greater potential marketing uccess," 08 2007.

[16] R. Bergström, Interviewee, *Hydraulic Design Engineer.* [Interview]. 2018.

[17] H. Products, "HPR Micro Reversible Powerpacks," Hydra Products.

14.1 Verbal References

Bergström, Robin (September - November 2018). Hydraulic Design Engineer at TMHMS AB

Appendix A Workshop Plan

Workshop

This document describes the structure of the activity during the workshop

Group size: 3-6

Equipment: Whiteboard, several pens and pencils, A4-paper, Room (6-10 persons), sound recording device, pictures, coffee.

1. Welcoming 5min

Fredrik and Rasmus present themselves and asks all participants to do the same. The participants start off with filling out a form containing questions about what work they do. This is done so that we later can discuss around the diversity in the workshops. The general rules for brainstorming and brain writing are explained.

1. Criticism is not allowed
2. Freewheeling is encouraged
3. 1+1=3. Be inspired and inspire others
4. Quantity is sought

2. Warm-up Exercise 10min

A warm-up exercise will create a creative and safe atmosphere without criticism. The warm-up exercise is a paper airplane game. Each participant gets a piece of paper and has four folds to create a paper airplane while constantly touching the paper with both hands. When everyone has completed four folds the paper airplane is passed on to the next participant who gets to finish det airplane with unlimited folds but still constantly touching the paper. The latter folder “owns” the design and all airplanes compete in a distance throw.

The participants will not get the information about passing on and finishing another one’s airplane until the four folds are complete.

3. Brainstorm 15min

The specific rules are explained. A facilitator stands in front of the whiteboard with whiteboard pens, post-its and printed pictures of common technical solutions. The facilitator asks the group “berätta alla sätt eller lösningar som medger att något förflyttas i höjdled”. The idea/technical solution/concept is illustrated on the whiteboard. If needed the facilitator asks the participant to elaborate. When the question feels drained the facilitator ends the activity.

4. Problem Statement 5min

The background of the project and the problem is presented. The problem statement should guide thoughts towards the specific situation, not create obstacles that could hold back any aspiring ideas.

5. Brain writing (Drawing) 40min

The specific rules are explained. Every participant is supplied with a variety of pens and papers.

1. Every participant should for the next 3 minutes write and sketch down one concept for a compact lift mechanism. This is repeated three times. Emphasize that the concepts or ideas does not necessarily need to be new innovations. It is perfectly good to use existing technology in an existing, different, new or more compact way.
2. BREAK. The participants can fetch some coffee and fika.
3. The generated concepts are discussed, and the maker explains the thought.

The next step is chosen depending on the occurring situation and how much time it is left.

Rewarding discussions
Continue the discussions. Get to the bottom of ideas and thoughts, make participants elaborate.

Time exists and creativity flows
Every participant will for the next 5 minutes sketch a concept with a previous concept as inspiration. The generated concepts are discussed, and the maker explains the thought

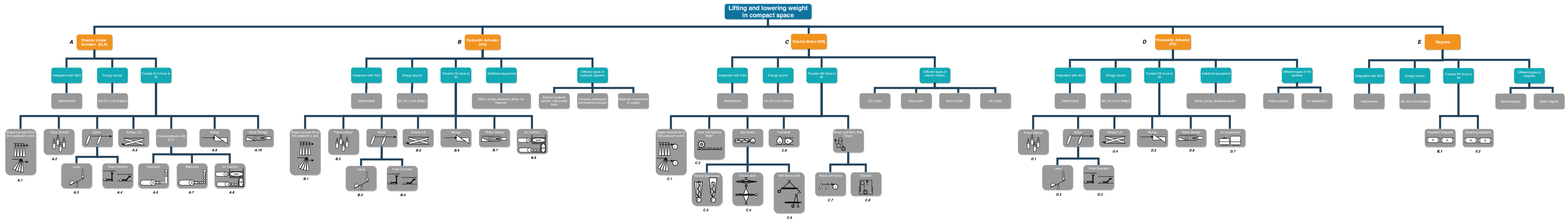
Time exists but creativity is not flowing freely
Every participant will be assigned one technical solution and should during 3 min generate a concept containing this solution. The sketch is then passed on to another participant that shall for the next 3 minutes evolve this concept with their own ideas. The generated concepts are discussed, and the maker explains the thought

Time exists but creativity is not.
All the generated concepts are discussed and then categorized according to similarity or other criteria. PMI-lists are made for a selection of the concepts/categories.

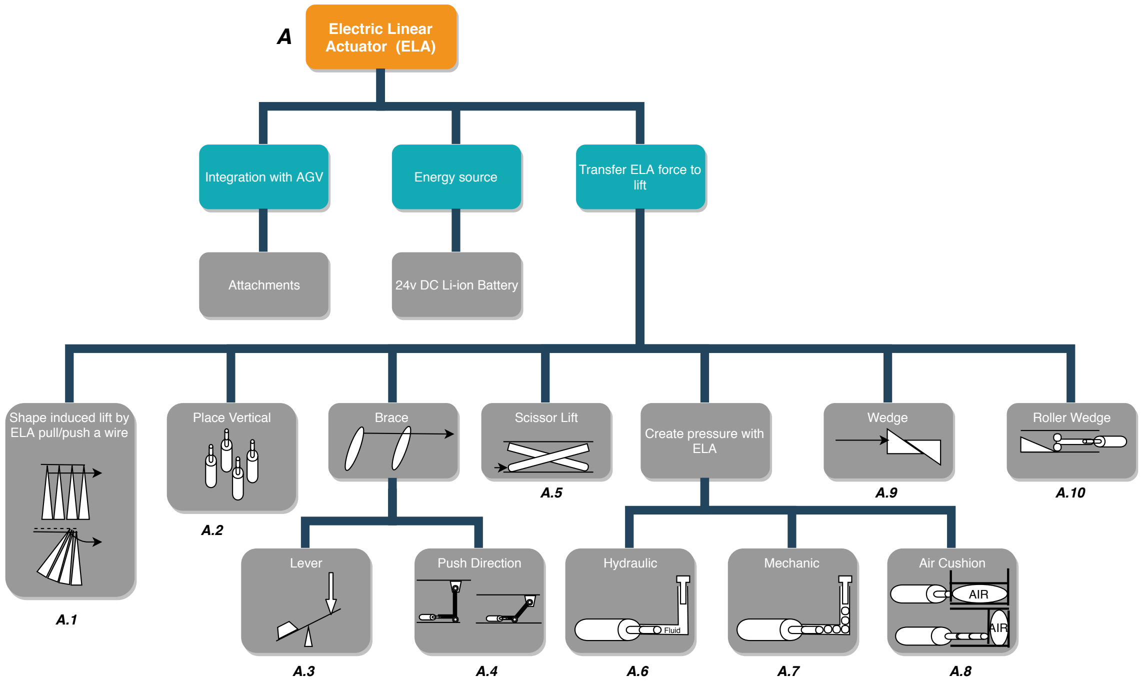
6. Closure 5 min

Thank the participants for their time. Ask for comments, questions or thoughts. Give them information of how to get in touch if something pops-up.

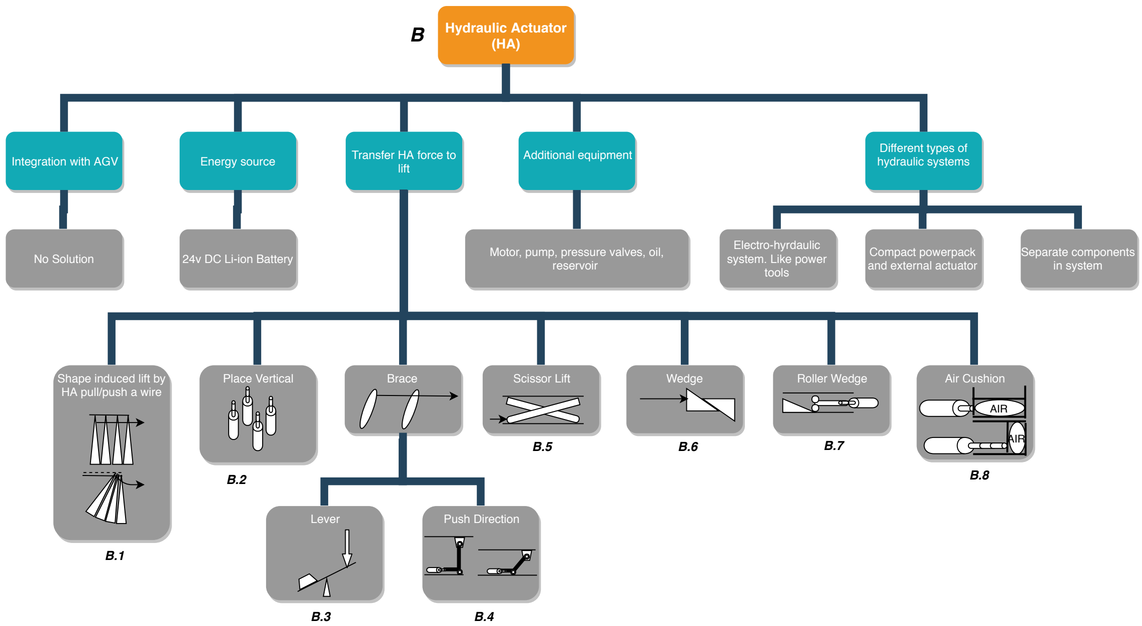
Appendix B Function Means Flow Chart



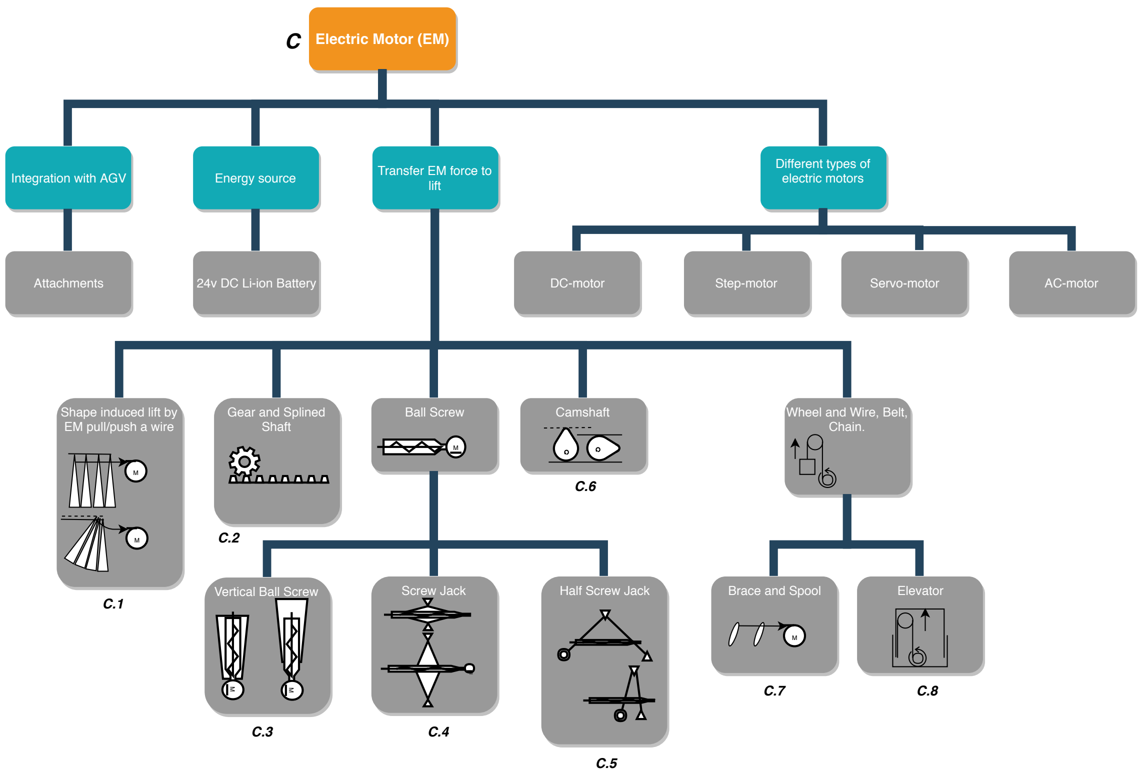
Lifting and lowering weight in compact space
A
Electric Linear Actuator (ELA)
Integration with AGV
Energy source
Transfer ELA force to lift
Attachments
24v DC Li-ion Battery
Shape induced lift by ELA pull/push a wire
A.1
Place Vertical
A.2
Brace
Lever
A.3
Push Direction
A.4
Scissor Lift
A.5
Create pressure with ELA
Hydraulic
A.6
Mechanic
A.7
Air Cushion
AIR
A.8
Wedge
A.9
Roller Wedge
A.10
B
Hydraulic Actuator (HA)
Integration with AGV
Energy source
Transfer HA force to lift
Additional equipment
Different types of hydraulic systems
Attachments
24v DC Li-ion Battery
Motor, pump, pressure valves, oil, reservoir
Electro-hyrdaulic system. Like power tools
Compact powerpack and external actuator
Separate components in system
Shape induced lift by HA pull/push a wire
B.1
Place vertical
B.2
Brace
Lever
B.3
Push Direction
B.4
Scissor Lift
B.5
Wedge
B.6
Roller Wedge
B.7
Air Cushion
B.8
C
Electric Motor (EM)
Integration with AGV
Energy source
Transfer EM force to lift
Different types of electric motors
Attachments
24v DC Li-ion Battery
DC-motor
Step-motor
Servo-motor
AC-motor
Shape induced lift by EM pull/push a wire
C.1
Gear and Splined Shaft
C.2
Ball Screw
Vertical Ball Screw
C.3
Screw Jack
C.4
Half Screw Jack
C.5
Camshaft
C.6
Wheel and Wire, Belt, Chain.
Brace and Spool
C.7
Elevator
C.8
D
Pneumatic Actuator (PA)
Integration with AGV
Energy source
Transfer PA force to lift
Additional equipment
Different types of PA systems
Attachments
24v DC Li-ion Battery
Motor, pump, pressure valves.
Piston actuator
Air suspension
Place Vertical
D.1
Brace
Lever
D.2
Push Direction
D.3
Scissor Lift
D.4
Wedge
D.5
Roller Wedge
D.6
Air suspension
D.7
E
Magnets
Integration with AGV
Energy source
Transfer PA force to lift
Different types of magnets
Attachments
24v DC Li-ion Battery
Electromagnet
Static magnet
Repellent Magnets
E.1
Attracting Magnets
E.2



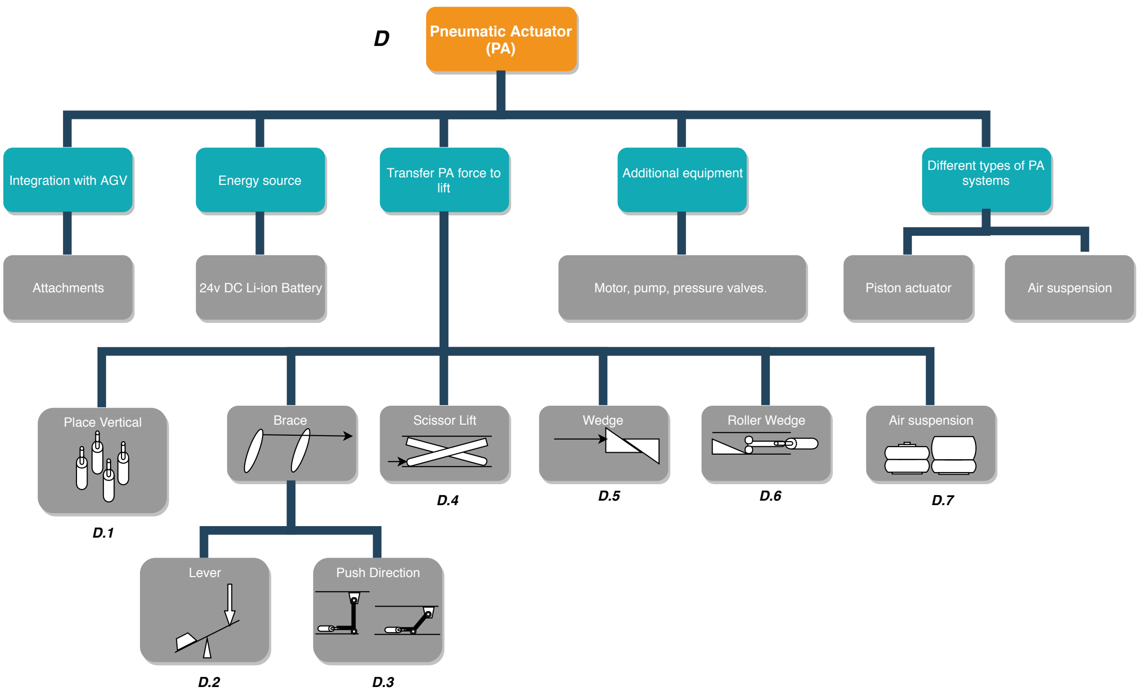
A
Electric Linear Actuator (ELA)
Integration with AGV
Energy source
Transfer ELA force to lift
Attachments
24v DC Li-ion Battery
Shape induced lift by ELA pull/push a wire
Place Vertical
Brace
Scissor Lift
Create pressure with ELA
Wedge
Roller Wedge
Lever
Push Direction
Hydraulic
Fluid
Mechanic
Air Cushion
AIR
AIR
A.1
A.2
A.3
A.4
A.5
A.6
A.7
A.8
A.9
A.10

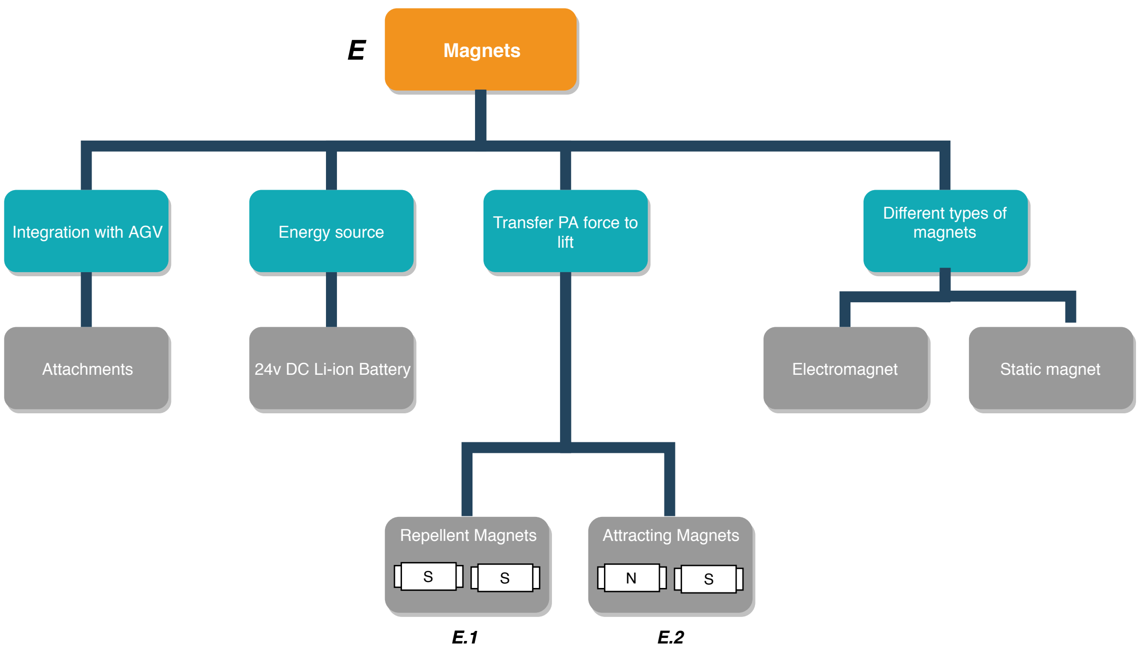


B
Hydraulic Actuator (HA)
Integration with AGV
Energy source
Transfer HA force to lift
Additional equipment
Different types of hydraulic systems
No Solution
24v DC Li-ion Battery
Motor, pump, pressure valves, oil, reservoir
Electro-hydraulic system. Like power tools
Compact powerpack and external actuator
Separate components in system
Shape induced lift by HA pull/push a wire
Place Vertical
Brace
Scissor Lift
Wedge
Roller Wedge
Air Cushion
AIR
AIR
Lever
Push Direction
B.1
B.2
B.3
B.4
B.5
B.6
B.7
B.8



C
Electric Motor (EM)
Integration with AGV
Energy source
Transfer EM force to lift
Different types of electric motors
Attachments
24v DC Li-ion Battery
DC-motor
Step-motor
Servo-motor
AC-motor
Shape induced lift by EM pull/push a wire
Gear and Splined Shaft
Ball Screw
Camshaft
Wheel and Wire, Belt, Chain.
Vertical Ball Screw
Screw Jack
Half Screw Jack
Brace and Spool
Elevator
C.1
C.2
C.3
C.4
C.5
C.6
C.7
C.8


D
Pneumatic Actuator (PA)
Integration with AGV
Energy source
Transfer PA force to lift
Additional equipment
Different types of PA systems
Attachments
24v DC Li-ion Battery
Motor, pump, pressure valves.
Piston actuator
Air suspension
Place Vertical
Brace
Scissor Lift
Wedge
Roller Wedge
Air suspension
D.1
D.4
D.5
D.6
D.7
Lever
Push Direction
D.2
D.3


E
Magnets
Integration with AGV
Energy source
Transfer PA force to lift
Different types of magnets
Attachments
24v DC Li-ion Battery
Electromagnet
Static magnet
Repellent Magnets
S
S
Attracting Magnets
N
S
E.1
E.2

Appendix C Ranking of Function Means

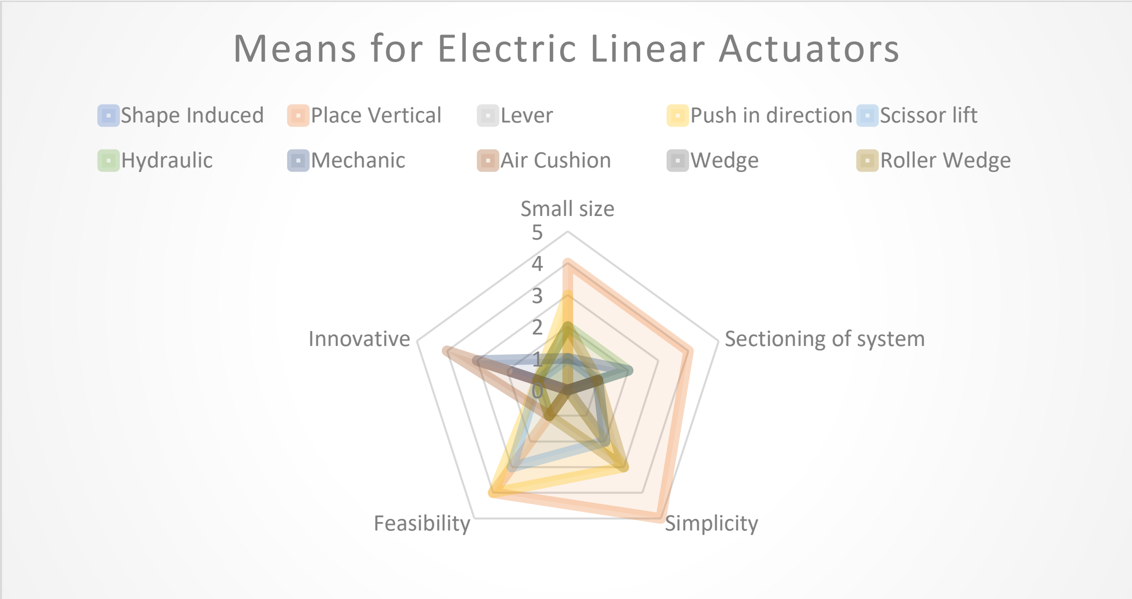


Figure 1 Means for Electric Linear Actuator illustrated in a spider chart

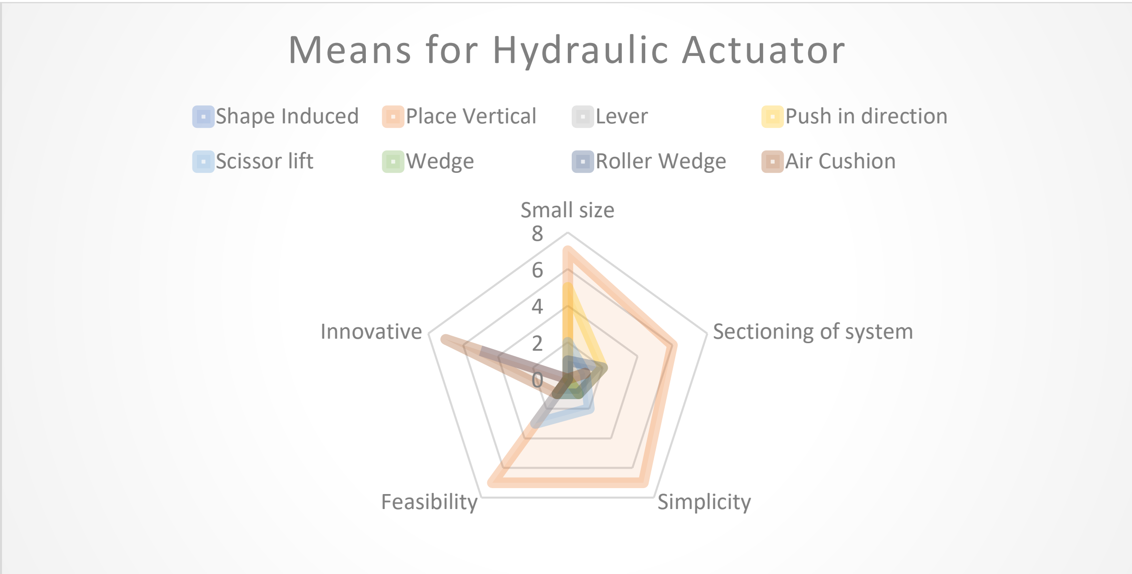


Figure 2 Means for Hydraulic Actuator illustrated in a spider chart

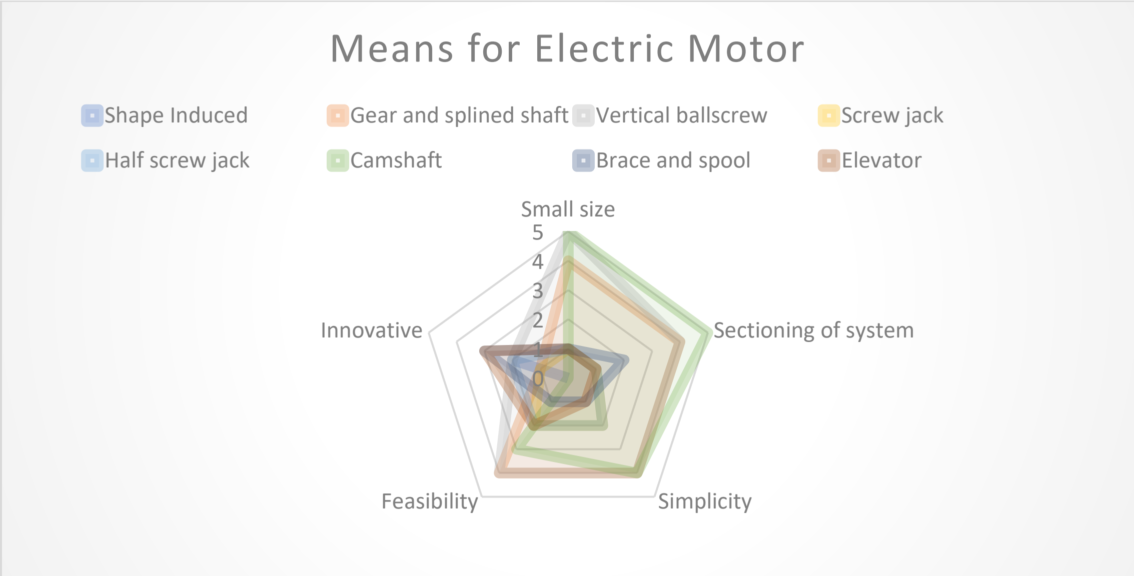


Figure 3 Means for Electric Motor illustrated in a spider chart

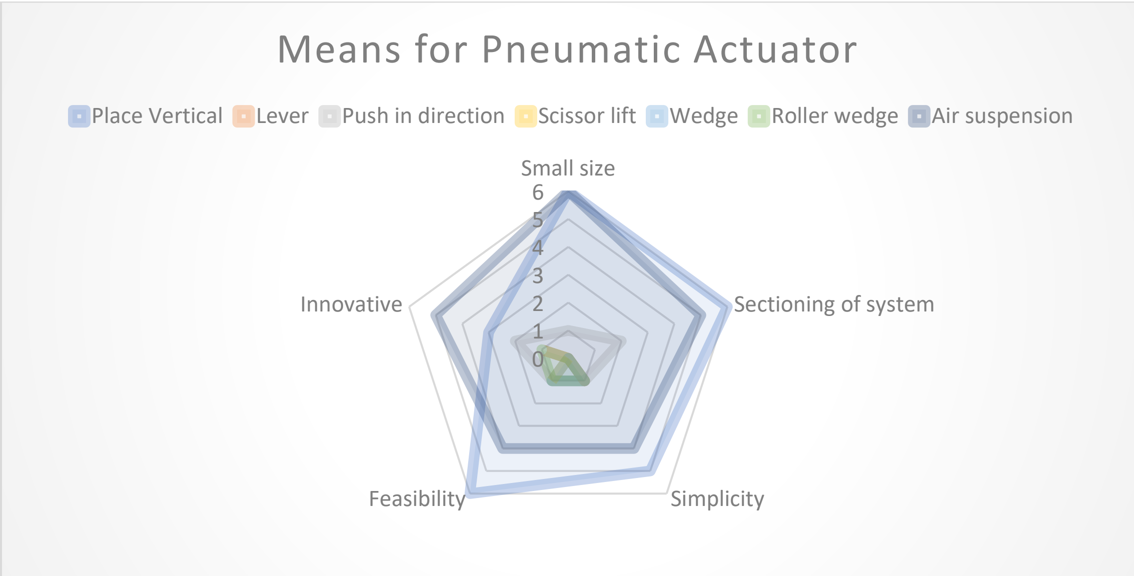


Figure 4 Means for Pneumatic Actuator illustrated in a spider chart

Appendix D Concept Development

Concept development

This document describes the concepts that was produced during concept generation and works as a foundation for the concept evaluation/selection.

Table of Contents

1 Reference Electric Linear Actuator

The identified force to lift a roller cage of 600kg is approximated to 6000N in a vertical force. Research was made of suitable linear actuators on market. The aspects of importance were size, strength, speed and the possibility of divide the force into multiple actuators. All electric actuators identified was too long to be placed vertical in a height of 120mm. Therefore, mechanical gearing was needed. Presented in concepts A1, A2, B, C, E2. An excel spreadsheet of different actuators was established where one actuator was seen more promising than the others.

Table 1Electric linear actuator comparison

Model	**Force [N]**	**Speed [mm/s]**	**Build in dimension [mm]**	**Height [mm]**	**Depth [mm]**	**Box volume [dm^3]**	**Force/ volume [N/dm^3]**
LA20	2500	10	220	46	36	0,36	6944
LA36	10000	10	300	148	76	3,37	2967
LA12	750	40	245	85	50	1,04	721
La23	2500	3,1	155	85	43	0,57	4413
DMA	2500	14	300	151	77	3,49	717
SCLA	800	7,6	195	82	43	0,69	1164
MD	5000	5	225	150	100	3,38	1481
HD24B068	6800	14	290	148	77	3,30	2057
HD24B045	4500	19	290	148	77	3,30	1362
Lambda	6000	5	277	97	55	1,48	4060
CAHB-22E	10000	10	325	151	76	3,73	2681
CAHB-21	4500	21	347	151	76	3,73	1206

LA20 form LINAK is a compact actuator with a cross section of 36x46mm and a build in dimension of 220mm. It can deliver a force of 2500N and with a combination of four LA20 it delivers 10000N in a volume of 1,44dm^2 with the possibility to divide the force to different places. Compared to a SKF CAHB-22E which delivers 10000N in a volume of 3,42dm^2. The actuator LA20 was then selected as a reference actuator to be used when evaluating the different mechanical gearing concepts. The approximated speed of the actuator is 10mm/s. The lead time of an actuator is seen as relatively short as it is an existing product.

2 A1. Push Brace

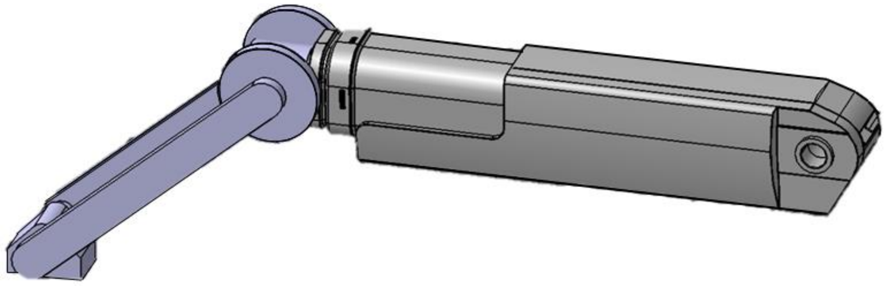


Figure 1Visualization of concept A1

2.1 Short description

An electric linear actuator applies a force on a connected brace to gain a vertical motion. The brace is connected in a fixed joint on one side and a moveable joint on the other. In the picture, the actuator is attached to the lifting platform to give space for other components beneath.

2.2 System components

- 2x Electric linear actuators
- Motor Control Unit
- 2x Brace

2.3 Functional representation and calculation

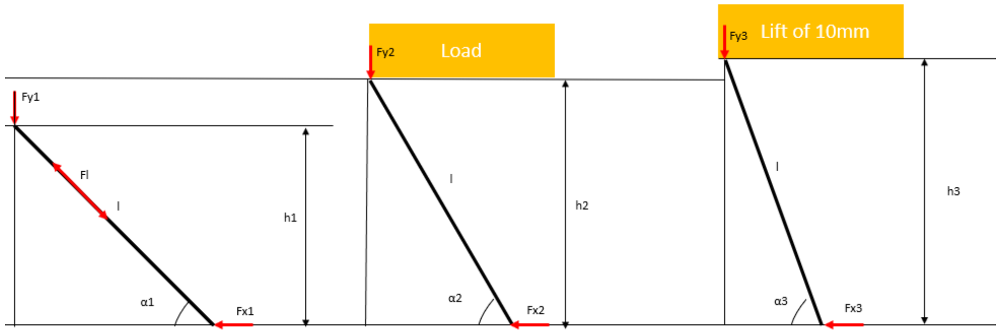


Figure 2 Calculation representation of concept A1

The length and angle of the brace determines the required force and stroke. If the angle is larger than 45° the leverage is advantageous. Shorter stroke requires a smaller angle and a higher force. If one brace is used with the length 125mm, a starting angle of 40°, an angle of 50° when loaded and the end angle of 66° a peak force of 4938N is required from the electric linear actuator to lift 600kg (with a favorable center of gravity).

2.4 Concept information

In a working situation the weight of the load will not be spread equally, this means that the center of gravity cannot be assumed in the middle, thus if two linear actuators and braces are used the predicted required force cannot be equally split between them. If the lifting mechanism is divided into several Considering the reference electric linear actuator LA20 four of these are required to generate the required force.

3 A2. Push Lever

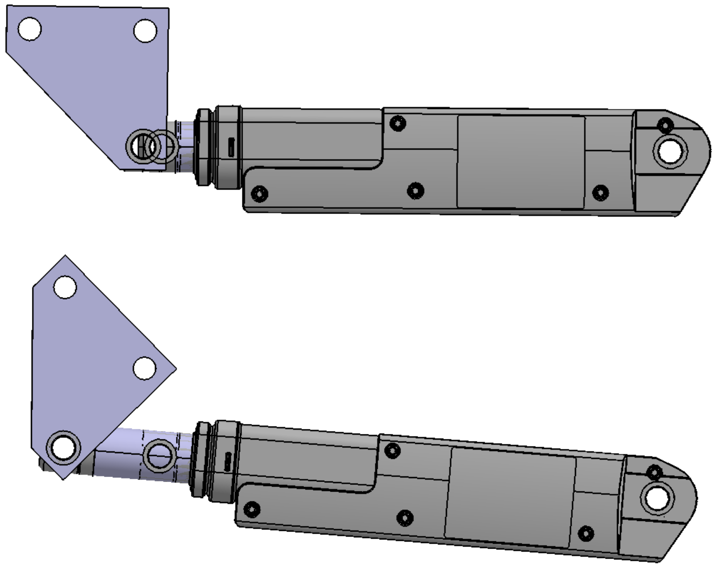


Figure 3 Visualization of concept A2

3.1 Short description

An electric actuator pushes a lever that transform horizontal motion to vertical. Force and speed can be modified by changing dimensions of the lever. A radial motion will occur and this need to be handled.

3.2 System components

- 3x Electric linear actuators
- 2x Motor Control Unit
- 3x Lever
- Vertical support

3.3 Functional representation and calculation

Following representation is a simplification of the concept to get an understanding of the load distribution, see Table 2 for calculation values.

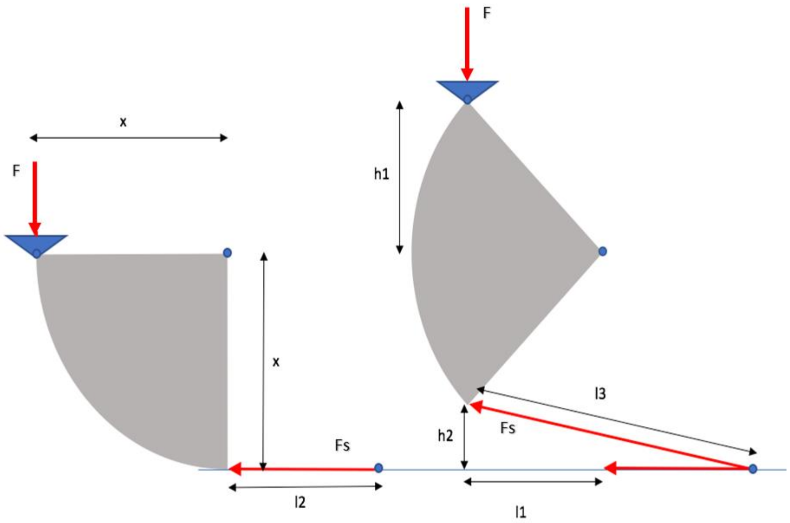


Figure 4 Calculation representation of concept A2

Table 2 List of values of concept A2

	ID	Value	Unit
Lever dimension	x	50	mm
Load force	F	6000	N
Lifting height	h1	35	mm
Actuator force	Fs (X)	6000	N
Horizontal stroke	l1	35	mm
Stroke	s	35	mm
Speed	v	10	mm/s
Lifting time	t	3,5	s

Equation 1

$$M: F * x - Fs * x = 0 => Fs = F$$
$$s \cong l1$$

3.4 Concept information

Initial calculations with gearing ratio 1:1 of the lever requires a force of total 6000N per actuator and the stroke of the actuator will be 35mm for a lift of 35mm. This will require 3,5s for one lift.

4 B. Scissor Lift

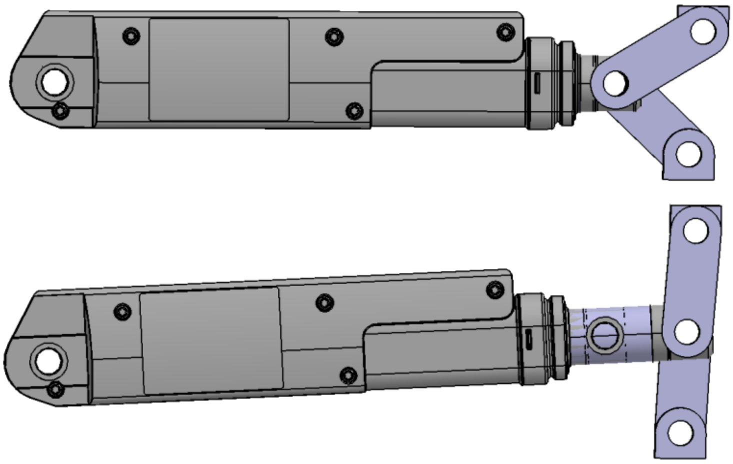


Figure 5 Visualization of concept B

4.1 Short description

An electric linear actuator pushes a “half” scissor lift. To get a more compact lift mechanism the scissor lift was divided into a “half” scissor lift.

4.2 System components

- 4x Electric linear actuators
- 2x Motor Control Unit
- 4x Scissor components

4.3 Functional representation and calculation

Following representation is a simplification of the concept to get an understanding of the load distribution.

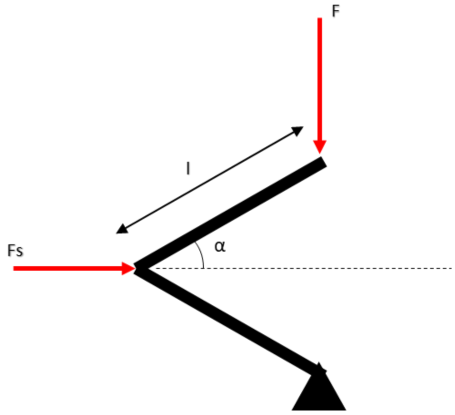


Figure 6 Calculation representation of concept B

Table 3 List of values for concept B

	ID	Value	Unit
Length	l	40	mm
Load force	F	6000	N
Lifting height	h1	35	mm
Actuator force	Fs (X)	10392	N
Angle	α	30	°
Stroke	S	31	mm
Speed	v	10	mm/s
Lifting time	t	3,1	s

Equation 2

$$Fs = \frac{\tan \alpha}{F} = 10392N$$

4.4 Concept information

The force required to lift depends on the starting angle. An angle of 30 degrees contributes to a total force of 10392N. With the dimension of 40mm of the sides the lift of 35mm is fulfilled by a stroke of 31mm at 3,1s. The load and speed can be varied by changing dimension and starting angle. One interesting thing about this concept is that if four actuators are used the load distribution can be calculated by logging the current from each actuator.

5 C. Roller Wedge

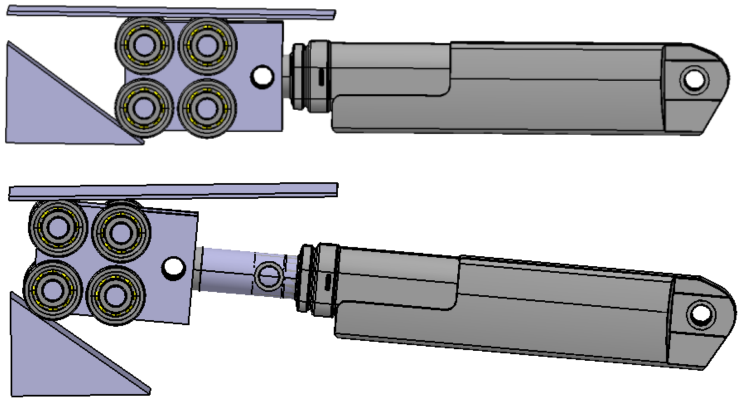


Figure 7 Visualization of concept C

5.1 Short description

An electric linear actuator is connected to a roller wagon that is pushed onto a wedge. The upper rollers will then push a lid vertical upwards.

5.2 System components

- 2x Electric linear actuator
- Motor Control Unit
- 2x Roller wagon
- 2x Ramp
- Vertical support

5.3 Functional representation and calculation

Following representation is a simplification of the concept to get an understanding of the load distribution. The stroke is calculated from the 3D-visualization model

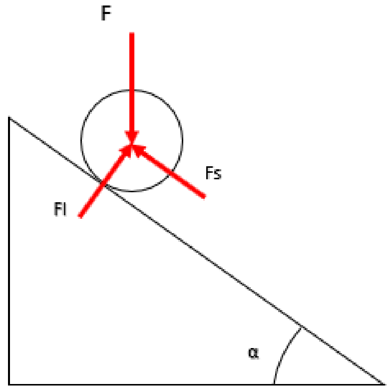


Figure 8 Calculation representation of concept B

Table 4 List of values for concept C

	ID	Value	Unit
Load force	F	6000	N
Lifting height	h1	35	mm
Actuator force	Fs (X)	3442	N
Angle	α	45	°
Stroke	S	51	mm
Speed	v	10	mm/s
Lifting time	t	5,1	s

Equation 3

$$Fs = \sin\alpha * \mathrm{F} = 3442N$$

5.4 Concept information

The force to lift the load is 3442N and can then be designed with only two actuators. Uncertainties in friction and angle variations will affect the force. This concept is seen as relatively complex with a lot of parts.

6 D. Place Hydraulic Cylinder Vertically

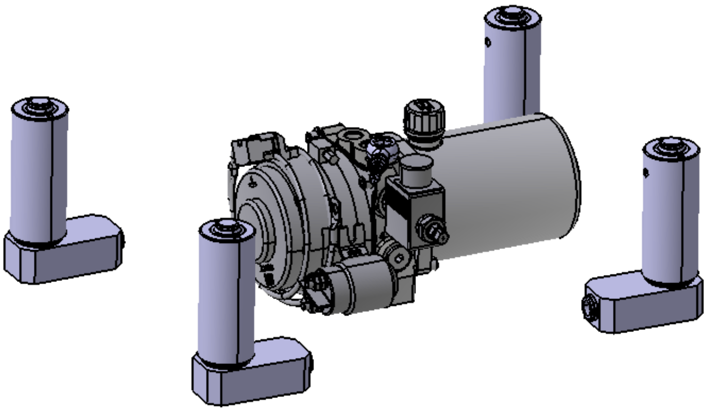


Figure 9 Visualization of concept D

6.1 Short description

A compact hydraulic system generates the force to elevate the cargo with hydraulic cylinders.

6.2 System components

- Pump
- Tank/Reservoir
- Motor
- 4x Cylinders
- Cables/pipes
- Valves

6.3 Functional representation and calculation

A hydraulic powerpack is a compact hydraulic system where the pump is often enclosed inside the tank volume. The other end is the electric motor.

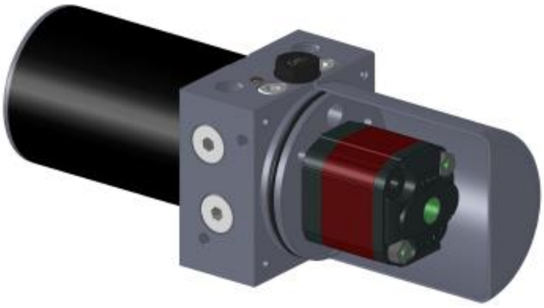


Figure 10 Picture of a power pack

The Toyota Autoshuttle is equipped with a compact hydraulic system, much similar to what is sought for in the ultra-compact AGV. The hydraulic system consists of a compact Micro Power Pack, tubing, fittings and four hydraulic cylinders. The Toyota Autoshuttle is larger in size than the ultra-compact AGV and can handle loads of 1500kg with margin of safety. Specifications of lifting time and information about duty cycle are unavailable but estimated to be similar. The hydraulic system in the Toyota Autoshuttle is considered to exceed the requirements set for a lift mechanism for the ultra-compact AGV except for size. This Micro Power Pack used in the Autoshuttle is over 130mm in height. The hydraulic system in the Autoshuttle is used as a guideline for further development.

According to Robin Bergström, Hydraulic Design Engineer, it would be enough to use one hydraulic cylinder with the piston diameter of 25mm pressurized by a pump up to 119Bars and the flow 0,5l/min to lift 600kg (produce the vertical force 6000N). The actual size of the hydraulic cylinder component is piston diameter +10mm. The above calculation is static and 15% should be added for dynamic situations. In the application of the AGV three or four hydraulic cylinders should be used to increase stability. In the case of several cylinders each cylinder can be made smaller than what was previously defined.

6.4 Concept information

The biggest component in this concept is the Power pack which comes in many different configurations. The smaller versions are shorter than 300mm with a diameter of about 100mm. The hydraulic cylinders are connected to the Power pack with flexible tubing which simplifies positioning. The system can be designed for sought speed at the cost of energy. TMHMS is very experienced in hydraulic systems.

7 E1. Air Cushion

Figure 11 Picture of air cushions

7.1 Short description

An electric linear actuator applies a horizontal force to an air cushion which deforms the air cushion and distributes the air vertically and creates a lifting force. To acquire enough lifting force, multiple electric linear actuators and air cushions can be used. To control the deformation of the air cushion a mechanical solution is required.

7.2 System components

- Electric linear actuators
- Motor Control Unit
- Air cushions
- Mechanic deformation controlling interface.

7.3 Functional representation and calculation

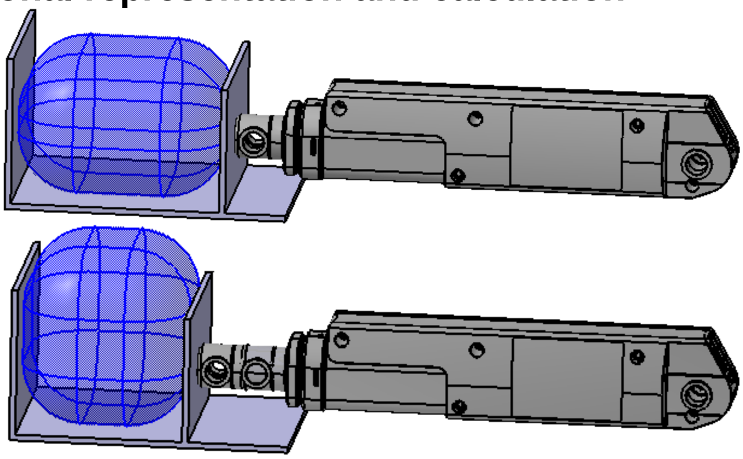


Figure 12 Visualization of concept E1

7.4 Concept information

Through internet research, Air cushions used in construction sites have been identified to be able to handle the given weight of 600kg. However, none of the identified air cushions are used in the manner described in the E1 concept. Every encountered air cushion produces a lifting force by being filled with a manual pump or electric compressor, often used for installation of certain objects such as windows. No information of how these air cushions behave when deformed by a pressing force is available. One other aspect of concern is how well the air is contained inside the air cushion. In the concept the air cushion is prefilled and never refilled. One can argue that custom made air cushions can be developed for the specific purpose. In that case knowledge of flexible materials is required as well as someone to manufacture the components.

8 E2. Enclosed hydraulic system with electric linear actuator

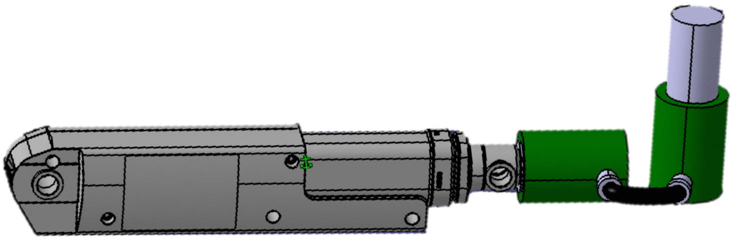


Figure 13 Visualization of concept E2

8.1 Short description

An electric linear actuator applies a force on a horizontal hydraulic cylinder which is connected to a vertical hydraulic cylinder which produces a lifting force.

8.2 System components

- 4x Electric linear actuator
- 8x Hydraulic cylinders
- 4x Reservoir/tank
- Pipes/tubes
- Couplings/fittings/connections

8.3 Functional representation and calculation

A force of 6000N is required to manage a lift. An enclosed hydraulic system has little losses.

8.4 Concept information

The hydraulic subsystem requires a reservoir of oil to keep the oil levels. The electric linear actuator and hydraulic cylinders can be designed or chosen to achieve desired force transmission and determines the systems speed and strength. A plausible linear actuator is the LA20 previously introduced with a length of around 220mm. According to Robin Bergström, Hydraulic Design Engineer, a hydraulic cylinder must be around 70mm plus stroke length. The resulting length of a linear actuator and a hydraulic cylinder will be minimum of 300mm, which in the context is considered very long. The tubing which connects the horizontal and vertical hydraulic cylinder is flexible, thereby simplifies the positioning of components. TMHMS is very experienced in hydraulic systems, but the combination of electric linear actuators and hydraulic cylinders has not yet been encountered.

9 F. Vertical Ball screw

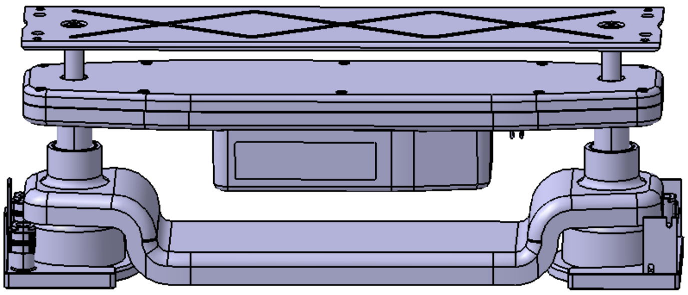


Figure 14 Visualization of concept F

9.1 Short description

Research of a suitable ball screw resulted in that there was no ordinary ball screw that could be fitted in the height of 120mm. One interesting similar solution was the Baselift from LINAK. Baselift is a module with two telescopic trapezoid screws that lifts parallel with a motor in the middle.

9.2 System components

- 2x Motor controller
- 4x Baselift

9.3 Functional representation and calculation

Technical specifications from datasheet:

- Force: 1500N
- Speed: 14mm/s
- Stroke: 100mm
- Built in dimension: 440x10x10mm

9.4 Concept information

To lift the load of 6000N there is a need of 4 Baselifts and the volume is relatively large. One important aspect is that the actual lifting mechanism is only the outer parts and the motor is placed in the box at the center of the Baselift. In a further development a customized Baselift could be more compact and probably be able to manage larger loads.

10 G. Camshaft

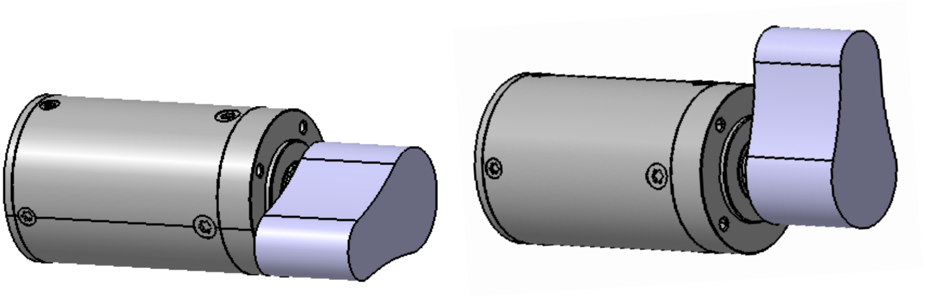


Figure 15 Visualization of concept G

10.1 Short description

Four or more cams is driven by two electric motors with gearing and rotates to push a top plate in a vertical direction.

10.2 System components

- Motor controller
- 2x Electric motor with gearing
- 4x Cams
- 2x linkage

10.3 Functional representation and calculation

Following representation is a simplification of the concept to get an understanding of the load distribution.

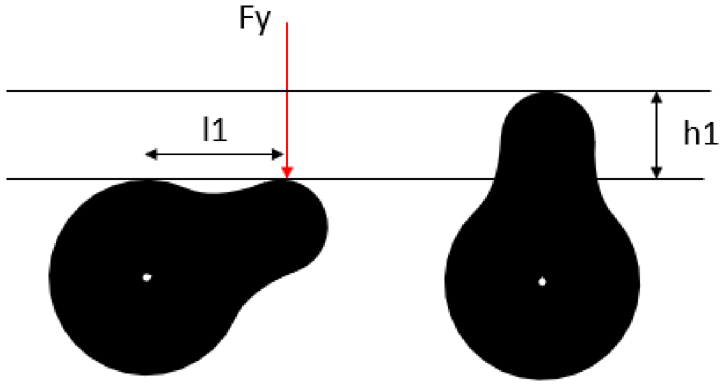


Figure 16 Calculation representation of concept G

Table 5 List of values for concept G

	ID	Value	Unit
Length	l1	60	mm
Load force	Fy	6000	N
Torque	M	315	Nm
Lifting height	h1	35	mm
Rotational speed	w	6,5	rpm
Lifting time	t	2,5	s

Equation 4

$$M = Fy * l1 = 315Nm$$

10.4 Concept information

A motor with nominal torque of 0,23Nm with a gearbox with gear ratio 710 will generate a torque of 163Nm. Two such motors will manage to rotate the cam to generate a vertical lift. With a nominal speed of 4600rpm it generates a rotational speed of the cam of 6,5rpm. To generate a lift the cam needs to be turned 90 degrees. The lifting speed will then be 2,5s. This system needs to be designed with a support that guides the top plate.

11 H. Air Suspension

Figure 17 Picture of a compressor system

11.1 Short description

An Air suspension kit designed for cars, including compressor and a remote controllable manifold is connected to four compact air springs. The compressor fills the air springs with pressurized air to gain a lifting force.

11.2 System components

The identified air suspension kit includes a compressor, a remote controllable manifold, a remote and some tubing. Four suitable air springs with associated couplings and tubing is required.

11.3 Functional representation and calculation

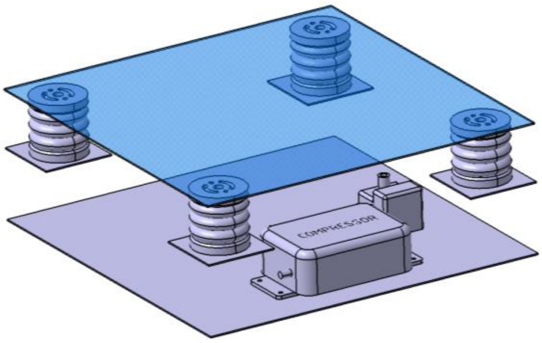


Figure 18 Visualization of concept H

11.4 Concept information

Air suspension is used in cars to adjust driving properties or to lower or raise the car body. Since these air suspension kits are designed for cars, they can handle heavy weights, more than 1000kg. The height adjustment is done in a matter of seconds. Several identified air suspension kits include all needed components and are designed for easy installation and can be installed without previous experience. These air suspension kits are considered as consumer products and can be purchased from several retailers with a short delivery time from a week to a few weeks. Flexible tubing simplifies the installation and positioning of the systems components. Technical specification which defines the different systems properties are hard to find, but reviews and instructional videos on YouTube indicates capability. No person at TMHMS with experience in air suspension or pneumatics have been found.

Appendix E Component Research

Electric linear actuator

Company	Model	Voltage [VDC]	Force Push [N]	Speed [mm/s]	Stroke [mm]	Feddback/Signal	Min build in dimension	Height	Depth	Comment	Link
LINAK	LA20	24	2500	3	50	Dual hall or hall potentiometer	220	46	36		LA20
LINAK	LA36	24	10000	10	100	LinBUS	300	148	76		LA36
LINAK	LA12	24	750	40	130	Dual hall or hall potentiometer	245	85	50		LA12
LINAK	Baslelift	24	1500	14	100	-	100	100	440		Baselift
Transmotec	DMA series	24	2500	14	102	Potentiomener	300	151,7	77,2		DMA
Servo city	SCLA	12	800	7,6	50	Potentiomener	195	82,5	43		Servocity
Motion dynamics	MD	12	5000	5	50	Limit switch	225	150	100		LZ-A01-50
Thomson	HD24B068-0100CNO1EES	24	6800	14	100	CAN bus	290	148	77		HD24B068
Thomson	HD24B045-0100CNO1EES	24	4500	19	100	CAN bus	290	148	77		HD24B045
RK Rose	Lambda	24	6000	5	100	Potentiometer	277	97	55		LAMBDA
SKF	CAHB-22E	24	10000	10,2	100	Encoder	325	151	76,5		CAHB-22E
SKF	CAHB21	24	4500	21	100	Encoder/Potentiometer	347	151	76,5		CAHB21

Ballscrew

Model	Force [N]	h [mm]	b [mm]	Link
NRS BF NW 8X2 (Planetary roller)	6980	41	41	NRS_BF_NW_8x2
MBN12X5R-3FW (Ball screw)	6850	28	37	MBN12X5R
903 RA W/PLASTIC NUT (Lead screw)	6895			903RA
903 RA W/BRONZE NUT (Lead screw)	13790			903RA_Bronze

Mini screwjack

Model	Force [N]	h [mm]	b [mm]	l [mm]	Link
E-series	5000	153	110	60	Powerjack
Mini cubic screw jack	2500	151	50	60	Kelston

Compressor and accumulator

Model	Link
Air Lift 25 870	Dalhems
ASG Ultrair Lufttank 48ci 3000psi	rodastjarnan

Air cushion

Model	Force [N]	Stroke [mm]	h[mm]	D[mm]	Link
TA Technix airspring 145mm short	-	120	80	150	TA Technix 145mm Short
Slam Specialities SS5	8829	149	100	140	Jebs SS5
Firestone 7076	4449,816	160	120	127	Product specification
Slam Specialities RE6	10300,5	180	760	152	Jebs RE6
PM/31022 Compact air bellows IMI	2130	45	65	95	imi-precision PM/31022
PM/31041 Single conv	5500	40	50	140	imi
Parker Hannifin 70mm bellow	-	50	-	80	Parker Hannifin produktblad

Hyraulic system

Model	Pressure [bar]	Power [W]	Tank volume [l]	h [mm]	b [mm]	l [mm]	Link
Hydraproducts	120	150	0,5	308	87		Hydrapro
Bucher UP40K1			0,5	446	80	103,5	Butcher datablad
Fluidlink-DC			0,2	239,5	86		Fluidlink

Hydraulic cylinder

Model	Force [N]	Stroke [mm]	h [mm]	b [mm]	Link
BVA HL2002	196200	44	97,5	90	BVA HL2002

Appendix F Follow-up Digital Form

Follow-Up Workshop

*Obligatorisk

1.

1. Vilken teknisk princip anser du vara bäst enligt följande kriterier (Välj 2 alternativ per rad) *

Markera alla som gäller.

	Electric Linear Actuator	Hydraulic Actuator	Electric Motor	Pneumatic Actuator	Magnets
Liten Volym	☐	☐	☐	☐	☐
Flexibel Placering / Modulläriseringsbarhet	☐	☐	☐	☐	☐
Låg Energiförbrukning	☐	☐	☐	☐	☐
Lyfthastighet	☐	☐	☐	☐	☐
Enkelhet	☐	☐	☐	☐	☐
Genomförbart innan årets slut	☐	☐	☐	☐	☐
Mest Innovativ	☐	☐	☐	☐	☐
Högst kraft i förhållande till storlek	☐	☐	☐	☐	☐

2.

Kommentar kring fråga 1

3.

2. Vilket medel anser du bäst passa en Electric Linear Actuator enligt följande kriterier (Välj 2 alternativ) *

Markera alla som gäller.

	A1	A2	A3	A4	A5	A6	A7	A8	A	A10
Liten Volym	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Flexibel Placering / Modulläriseringsbarhet	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Enkelhet	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Genomförbart innan årets slut	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Mest Innovativ	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

4.

Kommentar kring fråga 2

5.

3. Vilket medel anser du bäst passa en Hydraulic Actuator enligt följande kriterier (Välj 2 alternativ) *

Markera alla som gäller.

	B1	B2	B3	B4	B5	B6	B7	B8
Liten Volym	☐	☐	☐	☐	☐	☐	☐	☐
Flexibel Placering / Modulläriseringsbarhet	☐	☐	☐	☐	☐	☐	☐	☐
Enkelhet	☐	☐	☐	☐	☐	☐	☐	☐
Genomförbart innan årets slut	☐	☐	☐	☐	☐	☐	☐	☐
Mest Innovativ	☐	☐	☐	☐	☐	☐	☐	☐

6.

Kommentar kring fråga 3

7.

4. Vilket medel anser du bäst passa en Electric Motor enligt följande kriterier (Välj 2 alternativ) *

Markera alla som gäller.

	C1	C2	C3	C4	C5	C6	C7	C8
Liten Volym	☐	☐	☐	☐	☐	☐	☐	☐
Flexibel Placering / Modulläriseringsbarhet	☐	☐	☐	☐	☐	☐	☐	☐
Enkelhet	☐	☐	☐	☐	☐	☐	☐	☐
Genomförbart innan årets slut	☐	☐	☐	☐	☐	☐	☐	☐
Mest Innovativ	☐	☐	☐	☐	☐	☐	☐	☐

8.

Kommentar kring fråga 4

9.

5. Vilket medel anser du bäst passa en Pneumatic Actuator enligt följande kriterier (Välj 2 alternativ) *

Markera alla som gäller.

	D1	D2	D3	D4	D5	D6	D7
Liten Volym	☐	☐	☐	☐	☐	☐	☐
Flexibel Placering / Modulläriseringsbarhet	☐	☐	☐	☐	☐	☐	☐
Enkelhet	☐	☐	☐	☐	☐	☐	☐
Genomförbart innan årets slut	☐	☐	☐	☐	☐	☐	☐
Mest Innovativ	☐	☐	☐	☐	☐	☐	☐

10.

Kommentar kring fråga 5

11.

Bör fjädrar användas för att samverka med vald teknisk princip? *

Markera endast en oval.

	1	2	3	4	5	
Inte Intressant	◯	◯	◯	◯	◯	Mycket Intressant

12.

Övrigt

____

____

____

____

____