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Design of a Swappable Battery System for a Low Voltage Urban Battery Electric Vehicle

Supervisors

Prof. Andrea TONOLI

Dr. Eugenio TRAMACERE

Dr. Stefano FAVELLI

Candidate

Xueyan CHEN S296338

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Design of a Swappable Battery System for a Low Voltage Urban Battery Electric Vehicle

Chen Xueyan

Abstract

With the rapid development of urban low-voltage electric vehicles (EVs) in fields such as short-distance travelling and logistics and delivery, the issues of range and charging efficiency are becoming more and more evident. The traditional fixed charging method has limitations such as long charging time and high cost of infrastructure construction, which affects the user experience and market penetration. In this thesis, an innovative battery swap system is designed for the M1 class of urban passenger cars, represented by the Fiat 500e. The study transforms the original 400V high-voltage power architecture into a modular 48V low-voltage system, which improves safety while providing greater scenario compatibility for battery swap operations. The study firstly systematically sorted out the strategies and patent layouts of the world's mainstream power swap technologies, classified and analyzed them from the viewpoints of battery module form, swapping method and interface design, which provided theoretical support for this design. Then, based on the existing structural boundaries of the vehicle, a variety of design options for the swap path are proposed and modelled and optimized iteratively by SolidWorks. In the design stage of the module and transpallet, the design of the structure, electrical interface and fixing mechanism of the transpallet system is completed by taking into account the actual core parameters and packaging limitations, vehicle boundaries, material strength and power support conditions. Its mechanical reliability is verified by finite element method. Finally, a prototype of the system is realized, which is suitable for the parallel arrangement of two battery modules and has the ability of precise guidance and fast locking. The research results have certain reference value for improving the service efficiency and energy supply convenience of urban low-voltage electric vehicles and also provide a design paradigm for the engineering of low-cost power swap technology.

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Another Autumn Has Arrived.

In the blink of an eye, four years at *Politecnico di Torino* have passed. It feels like just yesterday when I left my homeland during the pandemic to study abroad. Beyond nostalgia, I feel immense gratitude—for the challenges that shaped me, the experiences that enriched me, and the people who made this journey unforgettable. Above all, I am deeply grateful to my parents. Over these years, I have been studying thousands of miles away, with little time to be by their side. Their unwavering support and understanding have been my strongest pillar, giving me the courage to face any difficulties.

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Chapter 1

Introduction

1.1 Background of the Study

1.1.1 Current Development of Urban Low Voltage Electric Vehicles

With the aggravation of the global energy crisis and the increasing severity of environmental pollution, electric vehicles (EVs), as clean energy vehicles, have gained wide attention and rapid development worldwide. In recent years, the performance

of urban low-voltage electric vehicles has been significantly improved with the advancement of battery and motor technologies as well as control systems. Especially in the field of urban transport, low-voltage electric vehicles have become an important choice for short-distance travel, shared travel and logistics distribution due to their low energy consumption, low cost and good environmental characteristics. The market demand in these fields is strong and is expected to maintain rapid growth in the future. Low-voltage electric vehicles generally refer to small electric vehicles

with a rated voltage between 48 V and 120 V, including low-speed electric vehicles (LSEVs) and some light electric vehicles. However, compared with large electric vehicles, the low-voltage batteries used in small and light electric vehicles have problems such as short range, long charging time and limited battery life, which greatly affect the market penetration of the product and the user experience. [1]

1.1.2 State of the art of battery technology and the potential of battery swapping technologies

Batteries, as a form of energy storage, are the core components of electric vehicles, whose technical indicators directly determine the range, charging efficiency, safety and service life of electric vehicles. Currently, lithium-ion battery (Li-ion Battery) is the mainstream EV battery technology, which dominates the market by virtue of its high energy density, long cycle life, and low self-discharge rate. In addition, lithium iron phosphate (LiFePO) batteries are more widely used in low-voltage electric vehicles due to their high safety and lower cost.

However, the traditional fixed battery charging method has many disadvantages. The charging time is long, even with fast charging technology (which mostly uses high voltage), it still takes 30-60 minutes to charge to 80, while a full charge may take several hours. In addition, range anxiety still exists. Due to battery capacity constraints, the range of a small EV after a full charge is usually between 100-200 kilometers, making it difficult to meet the demands of some high frequency uses. After a long period of use, the battery capacity decreases, leading to a decline in range, which affects the overall performance of the vehicle. Also, charging facilities are limited, charging pile construction costs are high and charging networks are not yet fully universal, especially in residential areas, commercial centers and rural areas where charging is still a challenge.

Based on the above challenges, the Battery Swap System (BSS) has become a solution that has attracted much attention. By adopting a standardized and modular battery design, users can replace the battery in a short period of time, which significantly improves the efficiency of the vehicle and greatly expands the usage scenarios of low-voltage electric vehicles. Batteries can also be rented, so users only need to pay for the vehicle body when purchasing a vehicle, reducing the upfront investment. Besides, the centrally managed exchange station can monitor the battery health status, optimize the charging and discharging strategy of the battery, extend the life of the battery, reduce the waste of resources. The standardized battery interface design also makes it suitable for different vehicle types, such as low-speed electric vehicles, logistics vehicles, shared electric vehicles, etc., expanding the service range of the battery network in a modular way.

In recent years, governments and companies have increased their R&D and promotion of replaceable battery technology. For example, China's national policy supports the power exchange mode, NIO and other car companies have laid out a network of power exchange stations and gradually expanded to the field of low-voltage electric vehicles, 2,350 Power Swap Stations (including 747 along expressways) have been built as of 2023 [2]. In Europe, the government encourages low-carbon travel, and companies such as Gogoro and Silence have made breakthroughs in the field of two-wheeled electric vehicle power swapping.

Although power exchange mode has many advantages, it still faces some technical challenges. The standardization of batteries still needs to be resolved, with differences in battery interfaces, sizes and management systems between different brands and models, hindering large-scale promotion. Besides, the construction cost of the power exchange station is high and needs to be reasonably distributed in the power exchange network to ensure the convenience of users. In addition, battery management and recycling are also issues that need to be addressed in the future, including how to optimize battery life management, reduce the operating costs of power exchange stations, and realize battery recycling and reuse.



Figure 1.1: NIO Power's Charging and Swapping Network in China [2]

With the development of artificial intelligence, big data, fast battery charging technology and the Internet of Things (IoT), intelligent power exchange systems will become mature. In the future, combined with vehicle-to-everything (V2X) and automated swapping robots, automated and intelligent swappable battery systems are expected to become the mainstream energy supply method for urban low-voltage electric vehicles.

1.2 Content and methods of study

This study focuses on the core requirements for the design of low-voltage urban electric vehicle power exchange systems, builds a three-phase research system of 'problem identification-solution design-simulation verification', focuses on the two main lines of mechanical structure innovation and system reliability enhancement, explores the power exchange technology solutions adapted to urban application scenarios.

1.2.1 Study Logical Framework

The research follows the progressive path of 'starting from the pain points of the industry and extending to the engineering realization'. The innovation of this path lies in the deep combination of theoretical research and engineering practice: on the one hand, the direction of improvement is clearly defined through the analysis of the current state of the technology, on the other hand, digital tools are used to realize the rapid iteration of the design solutions, forming a closed-loop optimization strategy.

1.2.2 Core Research Content

Systematically sort out the global patent layout of power exchange systems and identify key technology locking areas. Use innovation methodology to explore potential technology paths, focusing on breaking through the patent barriers of core components such as module configuration and fast locking mechanism, to form a combination of independent intellectual property rights. Adopted digital design platform to implement multi-stage iteration:

1. Conceptual design: Propose multiple basic configuration options and evaluate their space use efficiency and structural feasibility.
2. Simulation optimization: screening the optimal scheme of stress distribution and displacement through finite element analysis, dynamically adjusting the boundary conditions to simulate the real power exchange conditions.

The design process focuses on two major conflicts: the balance between the simplified process and precise positioning required for fast battery swap and the reinforced structure of the equipment, as well as the co-option of the design objectives with the existing limits of Fiat 500e.

Chapter 2

Analysis of Existing Battery Exchange Technology Routes and Patent Status

2.1 Current status of research and application of swappable battery system

The current technology route of swappable battery system can be classified according to two criteria: battery pack form and battery swapping path.

2.1.1 Classification by Battery Pack Formation

According to the battery pack form, the swappable battery system is mainly divided into the whole battery pack and the separate box of battery pack. Passenger car field whole battery pack exchange and separate box battery pack exchange two technology routes are applied, the commercial vehicle field is mainly used in the separating battery pack type exchange.

The whole pack replacement mode enables energy replenishment by replacing the integral battery pack integrated into the vehicle's underbody. Battery packs are usually standardized and deeply integrated into the chassis structure, with high capacity and mass. This approach usually requires modifications to the vehicle chassis structure to adapt to the rapid installation and release of the battery pack. The advantage of whole pack replacement is that the replacement is rapid and can usually be completed in less than 5 minutes. In addition, battery packs are often designed to be conformal to the vehicle body structure, allowing for better space utilization. Also, since the battery is placed inside a protective shell, it is safer and more airtight. But due to the differences in the specifications of the battery packs of different models, standardization is difficult, and the generality of the battery packs is limited in some ways. The representative brand of this type of power swap in the passenger car segment is NIO. The brand has built many power swapping stations

nationwide in China to provide express power swapping services for its models.



Figure 2.1: NIO Power Swap Station 4.0 (supporting automated battery swap for multiple brands and different vehicle models, i.e. NIO, ONVO and all battery swap strategic partners)

In addition, the whole-pack exchange method is widely used in commercial vehicles, especially in large vehicles such as heavy-duty trucks and buses. These vehicles usually need large-capacity batteries to meet the needs of long-time, high-intensity usage. Currently, the whole-pack exchange technology for commercial vehicles is mature and can meet the demand for high energy density and fast recharge for large vehicles, reducing vehicle downtime and improving service efficiency.

The split-box power exchange system adopts a distributed energy module layout that breaks down the battery system into multiple standardized sub-modules, and each module can be dismantled and replaced independently. When swapping, only the battery module with low power needs to be replaced. The advantage of this approach is that the battery module standardization is high, easy to achieve universal interchange between different types of vehicles, and the cost of power exchange equipment is relatively low. But this mode of power exchange time is relatively long and the sealing and safety of the battery is relatively poor. The commercial application of split-box power exchange is currently in the early stage, limited by the battery capacity, split-box power exchange is only used in light commercial vehicles, such as light logistics vehicles, sanitation vehicles, etc.

The core difference between the whole battery pack and the split-box system is found in the system expandability and scenario adaptability: the former is more suitable for the scenarios with high degree of standardization and automation, and the priority of supply efficiency due to the high degree of integrated design; the latter, through the modular design, can better satisfy the market demand of diversified vehicles and flexible range requirements.

2.1.2 Classification by different battery replacement paths

According to the different ways of changing batteries, the power exchange technology of e-vehicles is mainly divided into three ways: top exchange, bottom exchange and side exchange. These technologies are used in both passenger cars and commercial vehicles, with their own technical characteristics and applicable scenarios.

Top-side swapping is the exchange of batteries through the top of the vehicle. In this mode, the battery pack is usually installed on the top of the vehicle or on top of the cabin, and the power exchange equipment uses steel cables to lift the battery pack and complete the swap from the top of the vehicle. The technical realization of this mode is relatively simple, as the steel cable has a certain degree of flexibility, the battery pack can be compatible with a certain degree of error when it is positioned, so the power exchange station has a lower requirement for precise positioning, and the system cost is lower than that of other power exchange modes. Especially in closed scenarios such as harbors, mines and logistics transport, drivers can accurately complete the power exchange operation after enhanced training, allowing the control system to be relatively simplified, thus further reducing costs.



Figure 2.2: Top- swapping in the heavy commercial vehicle field

However, the degree of automation and intelligence of topside switching is low, and the process of swapping relies on manual operation, which requires a high level of driver skills, and therefore has limited potential to increase the speed of swapping in large-scale, high-frequency operation scenarios. Also, due to design constraints such as vehicle body structure and center of gravity arrangement, this method is difficult to apply to passenger cars and is more suitable for specific types of heavy commercial vehicles, such as mining trucks and harbor tractor trucks. In these areas, top-swapping occupies a certain market share due to its low cost and feasibility of technological realization, but the overall market size is still small due to the limitations of automation.

Bottom-side swapping is one of the most widely used current EV swapping technologies, with the core principle of removing and replacing battery packs through the bottom of the vehicle. In this mode, the battery is usually installed in the chassis of the vehicle, and when it is exchanged, the power swapping equipment enters from underneath, removes the old battery pack, and installs a fully charged new battery pack. Due to the relatively fixed structure of the vehicle chassis, the equipment in the power exchange station needs to have a high degree of accuracy to ensure that the batteries can be stably installed after the alignment of the interface, which puts

high demands on the mechanical structure, sensing system and automation control of the power exchange equipment.

Compared with top-side swapping, bottom-side swapping has a higher degree of automation, can complete accurate swapping through mechanical arms or lifting devices, reducing the impact of manual operation on the swapping efficiency, while the swapping process can usually be completed in 3-5 minutes, which significantly shortens the vehicle replenishment time, thus it is especially suitable for scenarios requiring high-frequency power swapping. This is the main reason why the technology has been widely used in the passenger car market. Also, because the battery is arranged at the bottom of the vehicle, the center of gravity is lower, which is conducive to improving the driving stability of the vehicle, especially in high-speed driving and cornering with better dynamic performance.

In the field of commercial vehicles, bottom-exchange also has a wide range of application potential, especially in urban logistics vehicles, sanitation vehicles and other areas that require high-frequency replenishment of energy. Compared with traditional charging methods, bottom swap can minimize vehicle downtime due to charging and improve operational efficiency. But compared with the top power exchange, the construction cost of the bottom exchange station is higher, mainly because the program requires accurate mechanical equipment, the adaptability of the vehicle chassis structure, as well as higher requirements for the unified standard of the battery pack. Although technology is still the main development direction of the current power exchange mode, as the bottom power exchange program can improve the efficiency of power exchange while ensuring the degree of automation.

In terms of the overall market, the bottom swap, with its high efficiency and stability, occupies a large share of the market and has become one of the main technologies used by a few mainstream passenger car brands (e.g., NIO as 2.1). In the commercial vehicle market, the bottom swap has also shown strong competitiveness and is likely to further expand its application scope with the development of standardized technology. But the future development still needs to solve the problems of high construction cost of power exchange stations and non-uniformity of battery pack sizes in different vehicles.

Side swapping is a kind of swapping technology that replaces batteries through the side of the vehicle, which usually sets aside standardized battery compartments on both sides of the vehicle chassis or on the side of the vehicle body, and when swapping, a mechanical arm or a guide rail system extracts the exhausted batteries from the side and inserts fully charged new batteries. Compared with both the bottom and top swapping, side swapping has certain advantages in terms of the complexity of the swapping equipment and the land area of the swapping station and is especially suitable for swapping places with limited space, such as urban distribution centers, express logistics sites and some public transport facilities.

The mechanical structure of side power exchange is relatively simple, mainly relying on horizontal sliding rails, mechanical arms or manual assistance to complete the battery swap, so the construction cost of its power exchange station is usually lower than that of the bottom power exchange, but it still requires a certain degree of automation adaptation compared to the top power exchange. Since the battery is replaced on the side of the vehicle, the interface of the power exchange operation is usually lower, this feature reduces the precision requirements for the power exchange equipment, thus reducing the cost of equipment maintenance.

Meanwhile, side switching also makes high demands on vehicle design, the body structure must reserve a suitable window for swapping. Since the interface is more exposed, it might be affected by the external environment, for example, rainwater and mud entering the battery compartment, which will affect the safety of battery connection. Therefore, compared with bottom swapping, side swapping requires higher sealing requirements in protection design. In addition, side swapping may have a certain impact on vehicle pass ability.



Figure 2.3: Side- swapping in light logistics vehicles and taxis

In the passenger car field, the application of side swapping is relatively rare, mainly due to the limitation of vehicle styling design and the traditional passenger car chassis layout is difficult to be compatible with side swapping ports. Similar to Botan Technology's application of side swapping in its commercialized vehicle power exchange solutions (as 2.3), the technology is mainly used in specialized operational vehicles, such as taxis, ride-hailing vehicles and some light logistics vehicles, but still faces standardization problems. In addition, the side switching mode has some applications in low-speed, fixed route vehicles such as light logistics vehicles, city delivery vehicles and sanitation vehicles, providing better flexibility and maintenance convenience.

In terms of the market, side exchange accounts for a relatively small share of the current power exchange market, mainly used in the field of light-duty commercial vehicles represented by light-duty logistics vehicles and some public service vehicles. Compared with the highly automated nature of the bottom power exchange and the low-cost advantage of the top power exchange, the side power exchange mainly

relies on its adaptability in specific application scenarios. But since the current construction standard of power exchange station is still dominated by the bottom power swap, the market expansion of the side swap mode is still facing challenges, the future development needs to further improve the standardized adaptability of both vehicle side and power exchange station and technically optimize the sealing, safety and generality of the interface of the power swap.

2.2 Patent Layout and Technology Analysis of Power Exchange System

The rapid development of electric vehicle power exchange technology has given rise to various patent layouts. Based on international patent data (including EP, WO, CN, US, etc.), this section analyses the overall design of the power exchange system, the structural design of the special battery compartment and module as well as the special battery interface and connection technology across three dimensions, systematically identifies their key technological innovations and discusses their respective strengths and limitations, evaluates the applicability and interaction of the existing patents as well as the possible evolution direction, providing technical references for the application of power exchange technology for the Fiat 500e's battery switching technology and the optimization of its adaptability to urban usage scenarios.

2.2.1 Overall design of the power exchange system

The overall design of the power exchange system focuses on the global architecture of the battery replacement process and the coordination of vehicles with the core objective of improving operational efficiency and scene adaptability. It mainly includes the design of the power exchange station architecture, the arrangement of the vehicle battery position, the logical design and optimization of the power exchange process as well as the design of equipment and tools dedicated to power exchange.

Early power swap technology is represented by US20100181129 (A1) [3], whose innovation consists in the use of a linear actuator-driven sliding battery rack (Fig 2.4), which allows the battery packs to be laterally withdrawn from the bottom of the vehicle through a multi-stage telescopic mechanism. The design ensures connection stability in bumpy conditions by means of a spring-loaded roller locking mechanism, which significantly improves the mechanical reliability of the power-switching operation in commercial vehicles. Advantages include simplicity, low maintenance costs and support for bi-directional battery pack insertion and removal to shorten the path. However, technology relies on stationary power exchange facilities, which are difficult to adapt to temporary charging points and the lack of standardization of battery pack sizes limits cross-vehicle model compatibility. Such fixed architecture provides the mechanical foundation of the switching process but exposes the tension between infrastructure dependency and scenario flexibility.

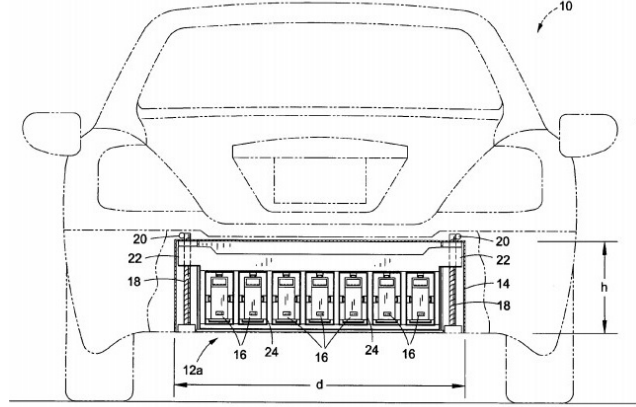


Figure 2.4: Sliding battery frame with linear actuator drive (source: [3])

As a complement to the stationary architecture, Patent US9358895(B2) [4] proposes a vertical lifting manual switching system, where the lifting and loading of battery packs for small passenger cars is done by a manually operated forklift (Figure 2.5). Its value lies in its compatibility with the compact space of private cars and its support for home charging. But its complete reliance on manual operation leads to inefficiency (an average of 15 minutes), and its lack of a battery status monitoring system poses safety risks. Patent CN209096692(U) [5] also focuses on manual operation and its design logic of precise positioning through mechanical limit structures (e.g., pin holes/pins, curved guiding surfaces) provides a reliable complement to automated systems.

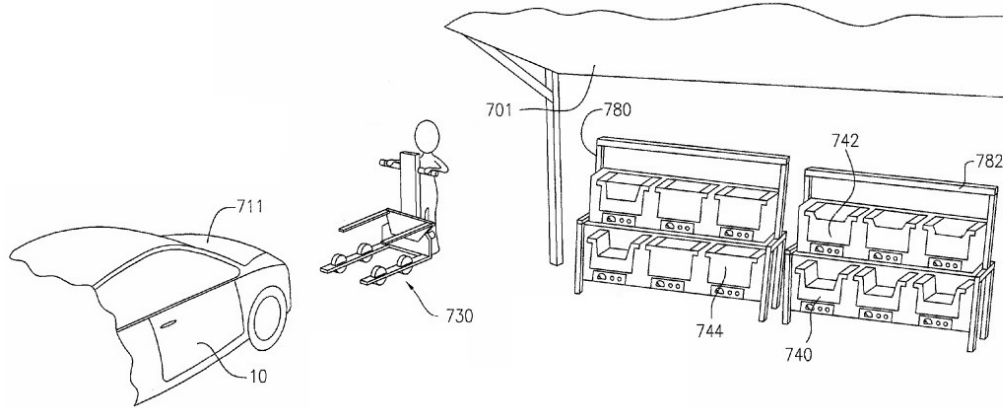


Figure 2.5: Vertical Lift Manual Power Exchange System (Source: [4])

To address the flexibility shortcomings of the fixed architecture, WO2010132775(A1)[6] miniaturizes the battery pack and integrates pulleys into a folding trolley structure, which allows the user to complete the changeover autonomously by moving it like a suitcase. The design extends the switching scenarios from dedicated stations to home and office environments, dramatically reducing infrastructure costs and making it particularly suitable for high-density urban areas. It eliminates the

user's reliance on lifting equipment and reduces physical exertion through the pulley design. But still need a suitable height difference environment to help power exchange and abandon the lifting equipment to limit the size of the battery module, limiting the efficiency of power exchange. On the other hand, patent WO2010070642(A1) [7] adopts the idea of making the power exchange station mobile for design, combining the lifting equipment and battery storage required for the integrated bottom power exchange with a flatbed truck trailer (Fig. 2.6), which promotes the generalization of the power exchange scenario. It achieves flexibility and rapid deployment while reducing space occupation and more efficiently meets users' power-switching needs at different times and spaces. These two patents mark the transition of power exchange technology from 'station centralization' to 'distributed mobility', but the lack of standardization and the problem of dynamic stability are still the main bottlenecks.

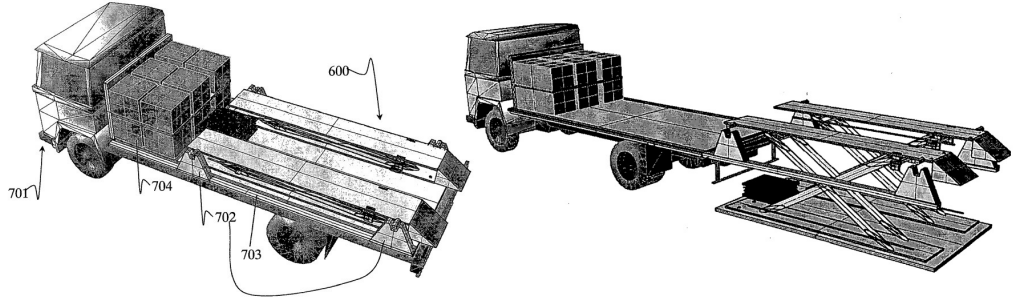


Figure 2.6: Design of a mobile power exchange station (Source: [7])

CN106143183(A) [8] also proposes a modular container architecture from the perspective of optimizing the space for power exchange and decoupling the functions of the physically separated power exchange platform and charging platform. Its innovation lies in the design of layered charging frame (charging layer, storage layer, mobile layer), combined with multi-stage guide rail system, which enables the power exchange trolley to freely dispatch batteries in both vertical and horizontal directions and significantly improves the space utilization rate. CN206436985(U) [9] integrates a rolling positioning device and an independent lifting mechanism (the front wheels and the rear wheels are lifted separately) in the power exchange platform, which is adapted to the chassis structure of different vehicle models. Compared with the vertical layering of the former, the patent achieves flexible deployment through planar rotation and extensible battery box. CN207790356(U)[10] is process simplification guided. Based on the former, it breaks new ground by eliminating the vehicle lifting step and instead adopts a floating mechanism to directly adjust the parallelism of the vehicle chassis, which compresses the overall height of the power exchange station to less than 400mm. The design breaks through the scene limitations and greatly expands the applicability of underground garages.

Patent US11400829(B1) [11] introduces an intelligent power exchange station ar-

chitecture based on cloud management, which achieves compatibility with multiple types of vehicles through standardized battery interfaces and dynamic adaptation algorithms on the vehicle side (Figure 2.7). Its core value lies in the introduction of digital twin technology to optimize the battery distribution path and enhance the efficiency of swapping decision-making through vehicle-station-cloud triple collaboration.

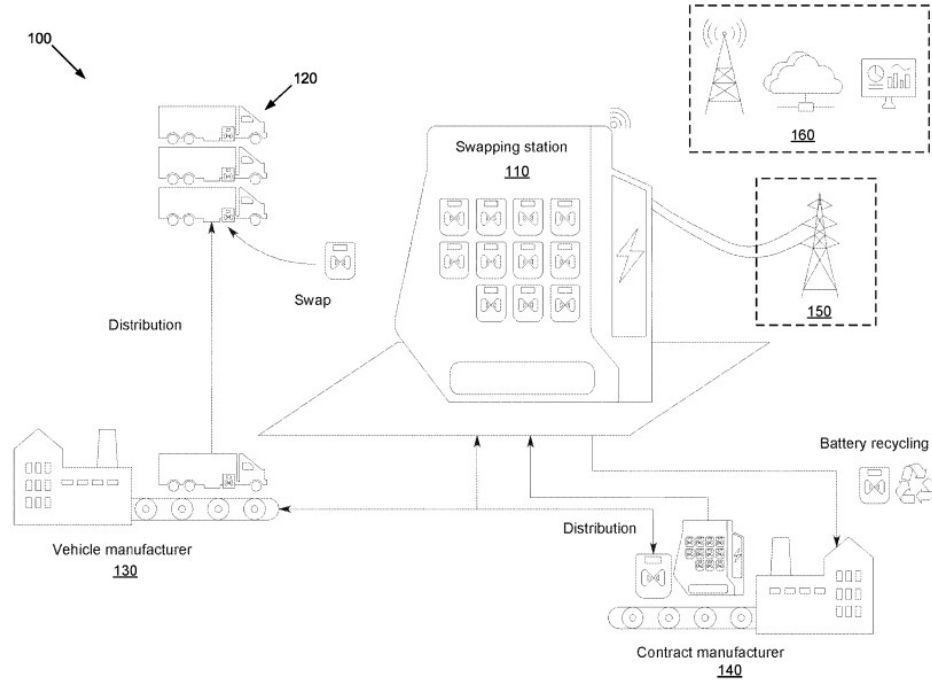


Figure 2.7: Architecture of a smart switching station based on cloud management (Source: [11])

Excellent design of the exchange station architecture is crucial to enhance the scalability and operational efficiency of the exchange system. The innovation of equipment and tool in the exchange process is also an important driving force to optimize the efficiency of the switching and to promote the exchange system. Patent US9358895B2 [4] achieves cross-vehicle compatibility through a standardized battery pack with an automatic locking mechanism. The battery packs are designed with a uniform interface size and are coupled to the vehicle's electrical contacts via a gravity-driven ball-pin locking mechanism (spring-loaded), which eliminates the need for additional tools during forklift loading and unloading (Figure 2.8). The core advantages are plug-and-play and high safety: the switching time of the battery pack between the charging post and the vehicle can be reduced to less than three minutes.

However, the standardized design sacrifices flexibility in terms of battery capacity (the range can only be extended by increasing or decreasing the number of batteries) and relies on dedicated forklift equipment, which is not sufficiently adapted to home

scenarios.

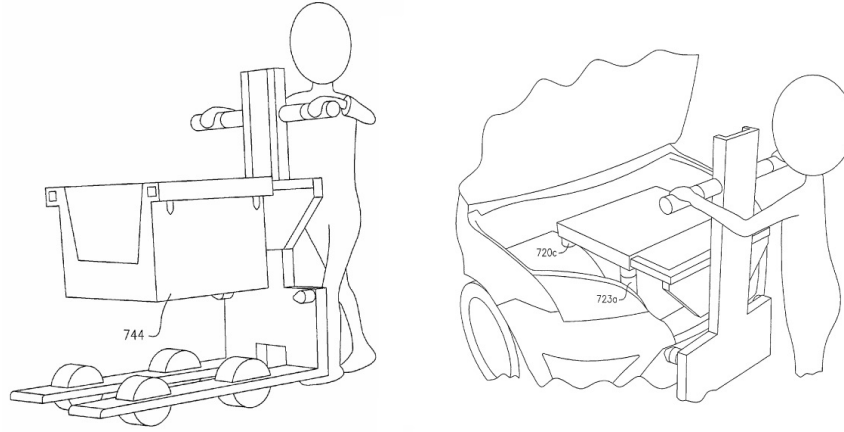


Figure 2.8: Standardized battery packs and dedicated forklift equipment (Source: [4])

Patent CN108928326B [12] focuses on the battery mobility needs of home scenarios and achieves seamless connection between the vehicle and the ground through a hydraulic synchronized lifting mechanism similar to a trans pallet, which greatly reduces the power exchange process dependence on infrastructure. But the battery pack positioning relies on manual visual alignment and the lack of precision may lead to interface wear. US11715858B1 [13] presents a mobile swappable battery system based on the optimized design of slide rails and handles, which reduces friction resistance and alignment errors in the traditional power-swapping method by introducing a slide rail system to make the insertion and removal of batteries smoother and to ensure the precise positioning of the batteries. Besides, the design supports the modular swapping method and can adapt to different types of batteries, which makes it popular to a certain extent. But the device occupies more space in the longitudinal direction and is suitable for the horizontal direction of the power exchange method and is difficult to match the bottom power exchange vehicle.

CN102180145(B) [14] proposes a foldable remote control power exchange system for emergency scenarios, whose core innovation lies in the integration of a modular scissor jack with remote control. Through the folding design of jacks in different positions, the storage volume of the equipment is compressed to 1/3 of the traditional power exchange station, which is suitable for the carrying demand of road rescue vehicles. The lifting platform trolley is equipped with a three-degree- freedom adjustment function, combined with laser positioning and camera detection to achieve accurate power exchange in unstructured environments. Similarly, patent CN208730782U [15] designs a battery frame lifting device with a scissor jack and ball pin synergizing for side power exchange vehicles (Figure 2.9). The motor drives a horizontal screw, converted to horizontal motion by a bevel gear to control the shear mechanism to lift the vehicle as a whole (maximum ground clearance 400 mm), while the battery frame is lifted and lowered independently to adapt to different vehicle models. The ball pin mechanism can compensate for the error of

multiple lifting points through self-balancing to ensure the stability of the vehicle after lifting. Its technical value lies in its high space efficiency and adaptive floating positioning. However, the scissor mechanism has a high demand for vehicle chassis structural modification and the mechanical complexity of the lifting mechanism, which is relied upon for multi-layer battery scheduling and may affect reliability.

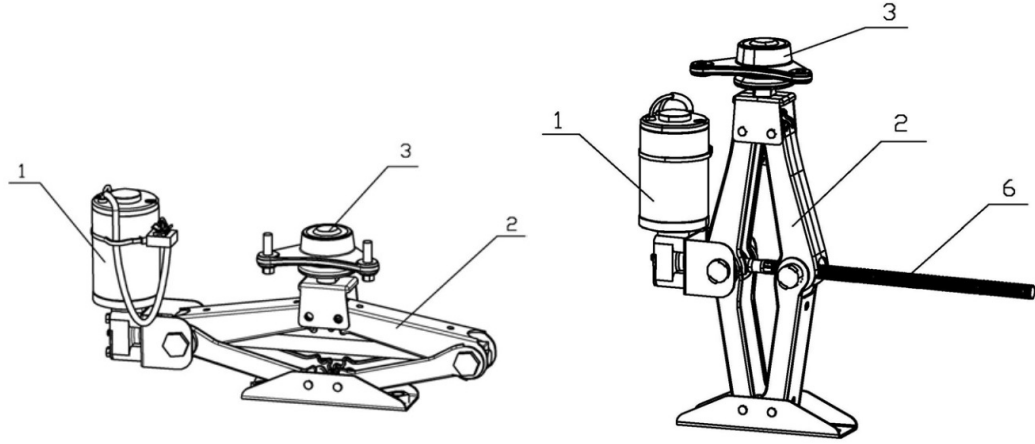


Figure 2.9: Lifting mechanism with scissor jacks in concert with ball pins (Source: [15])

CN209096692(U) [5] As a supplement to the automation system [8], the patent proposes a mechanical limit redundancy design, which reduces manual operation error through the combination of pin-hole mating and curved guiding surface positioning. The docking unit can be lifted and equipped with a deceleration and positioning belt to achieve coarse positioning and fine adjustment of the power change trolley. Its value lies in low cost and high reliability, which is especially suitable for emergency power exchange in case of automation equipment failure or special models in [8]. It is still designed for whole-pack power exchange with large loads, but it relies entirely on human operation (moving heavy batteries), which is inefficient and labor-intensive, thus it is only suitable for emergency situations and difficult to be promoted as a stand-alone power exchange system.

The power exchange system for electric vehicle battery needs to be designed to take into account the exchange speed, reliability, automation degree and compatibility, in which the holding mechanism of the power exchange equipment plays a crucial role in the exchange process. Patents CN106627517B [16], CN108556814B [17] and CN210822188U [18] use a linear slide, roller track and limit clutch visually positioned in combination with a vacuum suction cup to achieve the holding and releasing of the batteries respectively (Figure 2.10). Among these changing devices, both CN106627517B and CN210822188U have a high level of automation with the former focusing more on precise rail-based changing and the latter relying on visual positioning technology to achieve precise operation. In contrast, device CN108556814B has a slightly lower level of automation, but with its self-balancing mechanism and

assist arm design, it has greater adaptability in manual or semi-automatic power change scenarios. The core component of all three is a vacuum suction cup, which generates negative pressure through a vacuum generator to attach to the surface of the battery. Therefore, a dedicated pneumatic system is required as the power source of the suction cup. Thus, the three devices take up more space and are limited to specific places and their portability is poor.

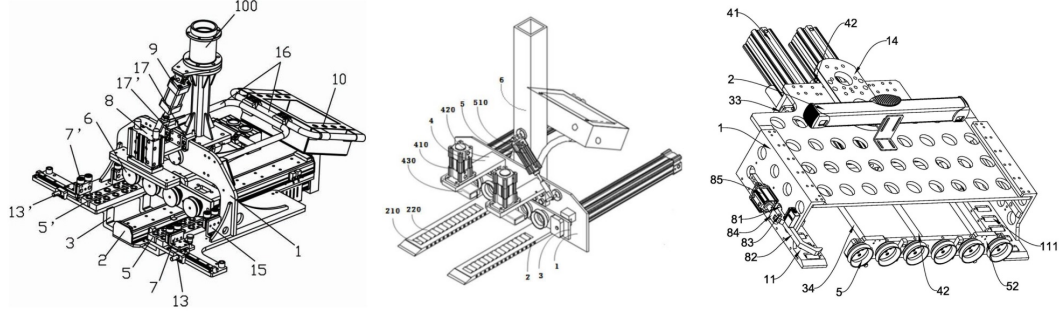


Figure 2.10: Lifting mechanism with scissor jacks in concert with ball pins (Source: [16] [17] [18])

The design of the power exchange system is a systematic project, which not only involves the power exchange site and equipment but also puts forward corresponding requirements for the battery arrangement of electric vehicles. A reasonable battery arrangement not only optimizes the power exchange process and improves efficiency, but also effectively balances the center of gravity of the vehicle, enhances driving stability and improves the safety performance of the vehicle. Patent CN109204057A [19] proposes an external battery box socket fixed on the vehicle for power exchange (Figure 2.11). The whole battery system consists of a fixed battery system and removable batteries. The removable battery system consists of a number of externally mounted individual battery packs, which can be removed and individually charged or exchanged by the user. But the capacity of the swappable batteries is small, and the switching efficiency is low. In addition, the external box design, which has a large impact on aerodynamics and has an unfavorable effect on safety, economy and aesthetics.

Compared to CN109204057A, CN109591565B [20] adopts a flexible battery pack design and incorporates a power-swap slide in the boot (Figure 2.12). The solution connects multiple battery packs by chains so that they can be bent within a certain range to suit the arrangement needs of different car models. The battery packs are housed in a hollow cavity in the vehicle chassis and are transported through the slide system. When the battery needs to be replaced, the slideway can be tilted downwards so that the battery pack can be slid out from the rear boot position for quick exchange.

The design has a high degree of automation for battery replacement, while maintaining the internal placement of the battery, thus reducing changes to the vehicle chassis

structure and providing better passive safety. The high complexity of the slide, expansion mechanism and transfer device components of this system may present cost and maintenance challenges in practical applications. Also, since the battery is arranged through the boot, it may affect the boot space of the vehicle and reduce the storage capacity of the vehicle.

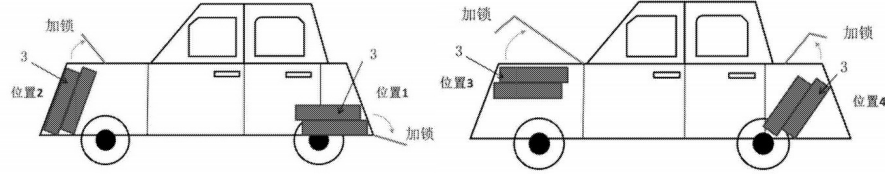


Figure 2.11: Batteries mounted in different locations on the outside of the vehicle (Source: [19])

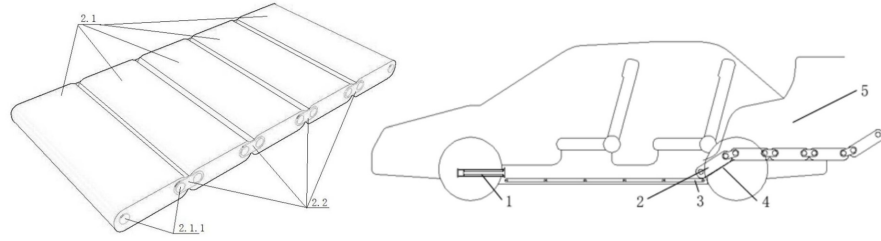


Figure 2.12: Flexible battery mounted inside the vehicle (Source: [20])

WO2021071412A1 [21] designed a more typical side swapping system (Figure 2.13). The innovation of the patent is the use of horizontally arranged changeable battery compartments, each of which holds only one individual battery module and can be pushed in or pulled out from the side of the vehicle. This approach allows for greater flexibility in the distribution of battery modules and allows the number of battery compartments to be adjusted according to vehicle size and user needs. The battery swap process, however, still requires its own or external mechanical equipment to lift and push out the battery compartments. The structural design of the vehicle also needs to reserve enough lateral space, which may affect the rigidity design of the body structure.

In the field of low-voltage swapping, the Spanish company Silence has adopted a swapping technology route that has attracted a lot of attention, with its unique design concept and efficient and convenient operation. By integrating a telescopic handle and a foldable wheel structure, its portable swappable battery realizes universal use between electric motorbikes and vehicles (EP2848456(A1) [22], WO2021144484(A1) [23], WO2022013471(A1) [24] as shown in Fig. 2.14). This compatibility design expands the range of battery applicability. Combined with the battery smart health system, mobile app and central server, users can realize remote booking and switching process control to improve the efficiency of the station. Based on the application of its sliding wheels with pull levers and the

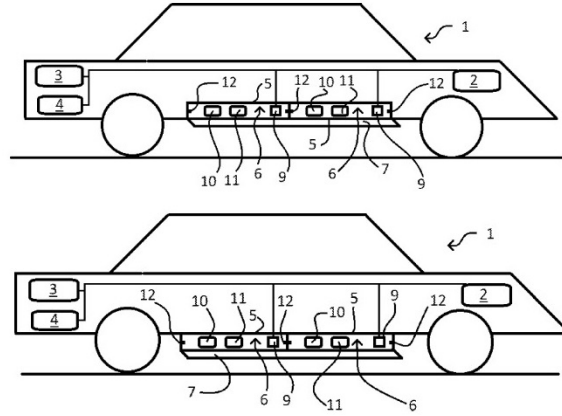


Figure 2.13: A side swap system (Source: [21])

side-mounted switching method, users can change heavier batteries on their own without having to move them vertically. The lateral mounting of the battery also reduces the pressure on the dirt and water resistance of the electrical interface to a certain extent. But the special lateral space under the seat also determines that the vehicle cannot be installed with more than two sets of batteries, and there is still a limitation in the cross-vehicle promotion of the power-swapping system. In order to simplify battery installation and removal, the rigid structure of the vehicle's sides has been compromised considerably, which may lead to a reduction in passive safety performance and affect the vehicle's impact resistance in a collision.

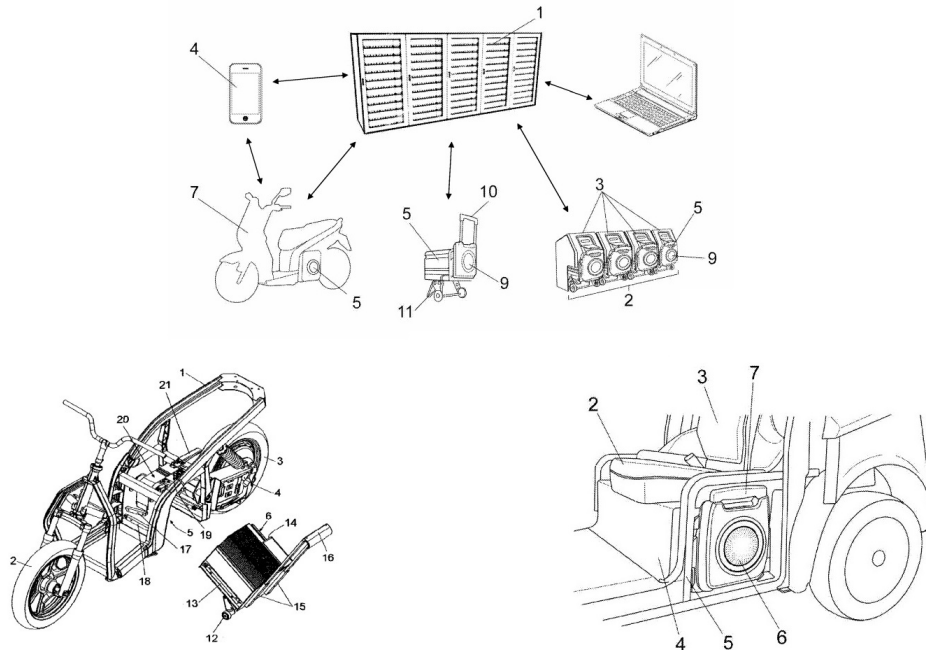


Figure 2.14: Silence's power swap system on the side (Source: [22] [23] [24])

2.2.2 Structural Design of Specialized Battery Compartments and Modules

The design of the battery compartment and module structure of the power exchange system mainly involves the standardization of the battery pack and its compartment, the design of the quick-change auxiliary mechanism and the design of the battery pack mobility solution. Patent CN107054040B [25] proposes a battery compartment structure with integrated elastic support members and roller guidance, which shares the load of the battery pack through a triangular elastic piece and combines with a vertical roller set to achieve fast sliding in and accurate positioning of the battery pack (Figure 2.15). An elastic-rigid composite support system is used to buffer vibration and ensure straight-line guidance when the battery packs are slid in. The end of the battery compartment adopts a wedge-shaped surface of the fixing frame and compression frame, which realizes the three-dimensional compression of the battery pack through the rubber elastic layer, simplifies the locking process and is suitable for lightweight battery packs for small passenger cars.

Patent CN203937650U [26] designed a modular battery compartment, using front and rear symmetric hatches and gear-linkage locking mechanism, through a single drive device (actuator motor) synchronous control of the opening and closing of the hatch and the battery locking to achieve rapid replacement of multiple battery packs (Figure 2.16). The design achieves automatic linkage of the hatch opening, closing and locking by meshing the drive gear with the sector gear of the locking mechanism. Its cross-shaped partition with equipped roller slides and nylon limit strips realizes the modularity of the battery compartment and supports parallel loading and unloading of multiple batteries. Unlike the gear linkage locking of CN203937650U, patent DE102015200388A1 [27] designs a rotary-translating composite battery compartment hatch mechanism (Figure 2.17). The mechanical linkage (e.g., hydraulic cylinder or rack and pinion) converts the rotational motion of the hatch into horizontal displacement of the battery module to achieve rapid battery replacement. Using the mechanical self-locking feature of the gear and rack or the hydraulic cylinder, the battery module is automatically locked after the hatch has been closed without any additional drive, which is highly reliable.

The mobility design of the battery of a power exchange system is a key factor in improving user experience and power exchange efficiency, different patents have proposed a variety of innovative solutions in this field. Among them, patent CN109203954B [28] allows traditional battery packs to be flexibly converted into movable units by allowing users to install or uninstall a pulley system according to their needs, which improves handling convenience and takes into account structural stability. CN212874661U [29] employs a combination of trolley bars and collapsible casters to keep the battery pack compact when not in use and quickly convert it to portable mode when it needs to be carried. This design enhances user convenience while maintaining space efficiency. WO2010132775A1 [30] further optimizes the

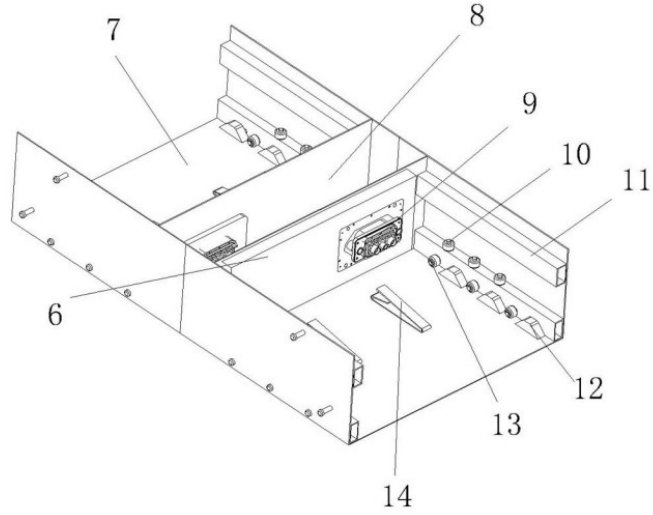


Figure 2.15: Elastic-rigid composite support and positioning system (Source: [25])

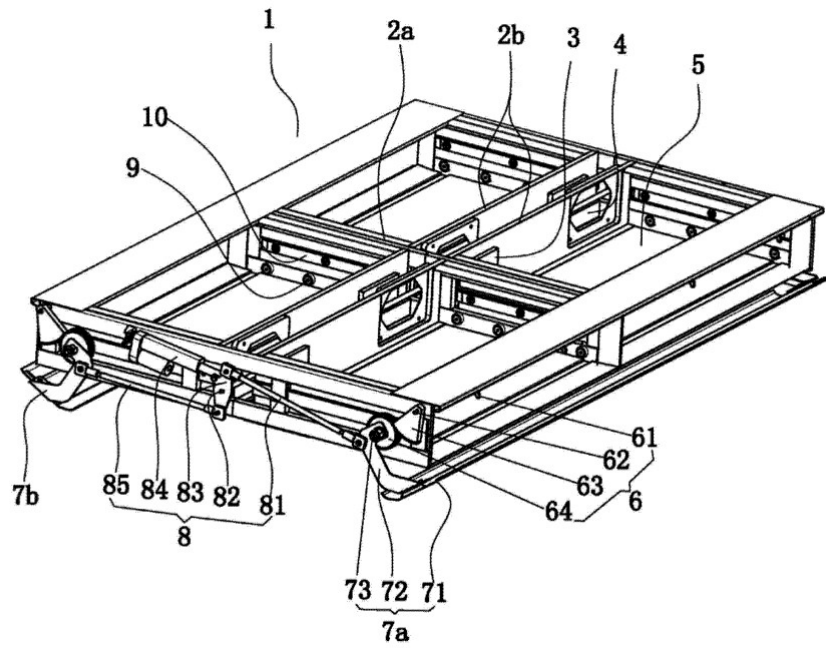


Figure 2.16: Modular battery compartment with hatch gear linkage locking mechanism (Source: [26])

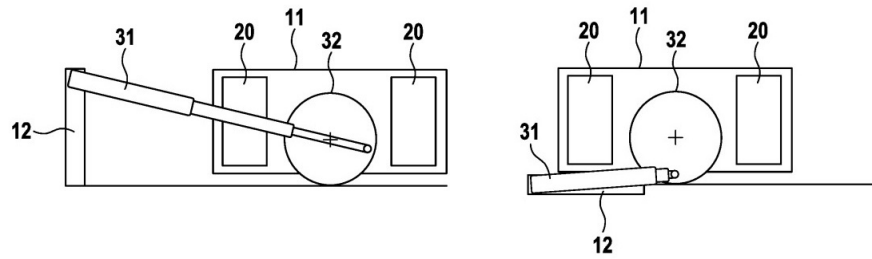


Figure 2.17: Rotary-translating composite battery hatch mechanism with self-locking feature (Source: [27])

ground mobility of the battery by adopting built-in pulleys and telescopic tie rods, which enable the battery pack to be moved to charging or exchange stations with little or no external force while designing quick-access and release interfaces to improve the efficiency of the exchange. These different mobility design options each have their own advantages in terms of user convenience, structural stability, manufacturing cost and on-ground adaptability (Figure 2.18).

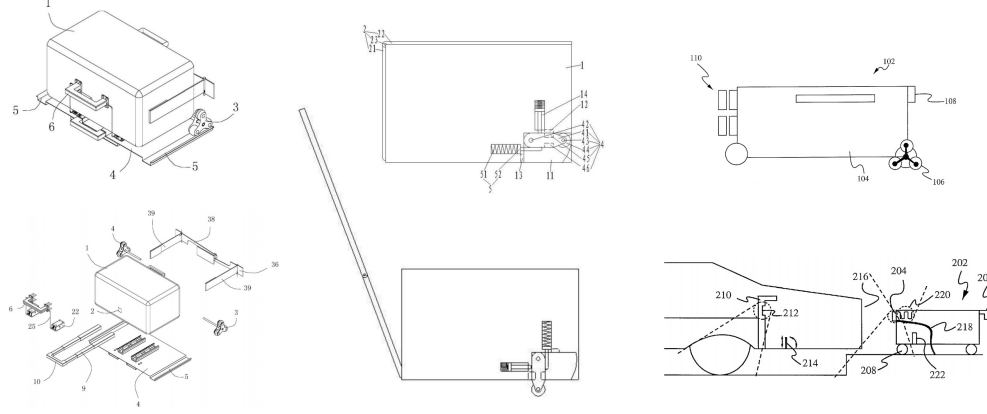


Figure 2.18: Three mobile battery pack designs (Source: [28] [29] [30])

2.2.3 Specialized battery interface and connection technology

Battery interface and connection technology mainly covers the efficient docking of batteries for charging and discharging, the design of locking mechanisms for batteries in different stages and compatibility optimization.

Patent CN205231137U [31] proposes a floating electrical connection seat, which realizes the fine adjustment of the socket position by means of an elastic structure, thereby improving the plugging precision and enhancing the vibration-resistant performance (Fig. 2.19). It solves the problem of low alignment accuracy of traditional fixed sockets by installing a sliding plate in the recess of the battery compartment and achieving lateral floating adjustment of the socket through evenly distributed springs or elastic fillers (e.g., honeycomb rubber). The symmetrical distribution of guide bushings on both sides of the socket, combined with the damping effect of the elastic structure, can maintain stable contact between the plug and the socket when the vehicle is bumpy. In the electrical interface design of WO2010132775 (A1) [32], a manual plug-and-play electrical connection is used. The battery pack is moved to the vehicle via a pulley structure and relies on mechanical locking and handle operation to complete the interface docking. The entire docking process requires manual operation by the user. Although the design is simplified, it lacks a precise positioning structure, and errors may occur when aligning the interface.

In patent CN211280706(U) [33], the electrical interface adopts the design method of precise positioning pin + electrical plug-in quick plug. The electrical connection

port of the battery pack is designed to be inserted in a vertical direction to ensure alignment accuracy by means of positioning pins and positioning holes in the vehicle or the power exchange station, which improves the efficiency of the power exchange and reduces errors. Moreover, the patent is additionally equipped with a water-cooled interface, which can be connected to the vehicle's thermal management system through a water plug-in to ensure the heat dissipation needs of the battery during high power usage, making the electrical connection more stable and reliable (Figure 2.20). This design is more suitable for automated power exchange stations and high-frequency battery replacement scenarios.

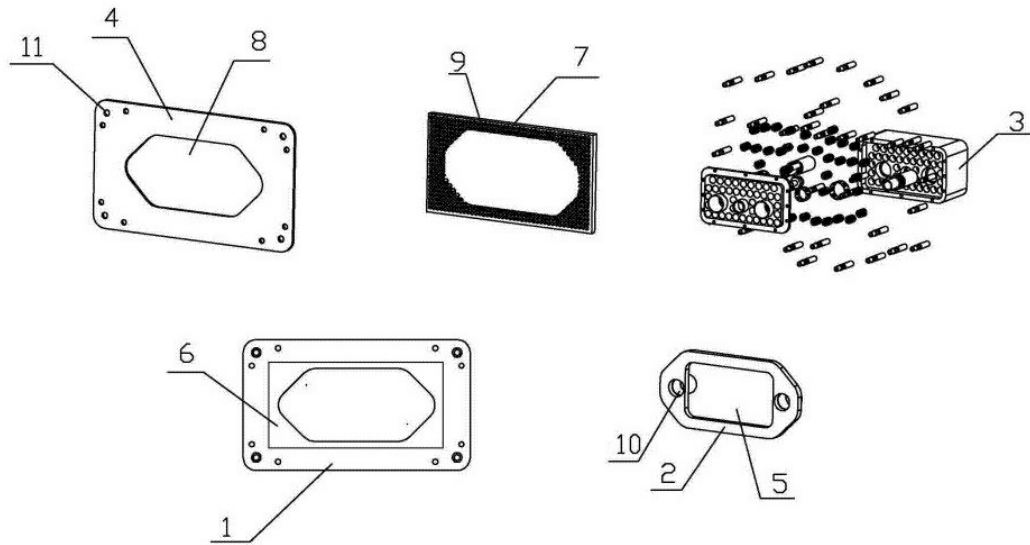


Figure 2.19: Floating Electrical Connection Seat (Source: [31])

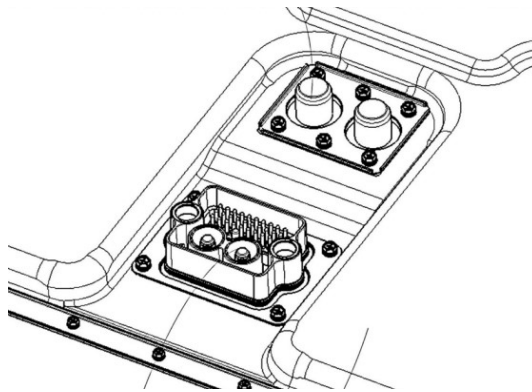


Figure 2.20: Electrical connection port with integrated water-cooling interface (Source: [33])

Regarding the locking mechanism of the battery, EP2280436(A2,A3) [34] proposed a removable battery pack with a core innovation of arranging the connection and locking mechanism at the bottom of the battery pack, utilizing the self-weight of the battery to ensure a stable electrical connection while achieving effective locking and fixing of the battery pack by a spring mechanism similar to a car door lock

(Fig. 2.21), which is simple and reliable in structure and has a low manufacturing cost. CN206250236(U) [35] proposes a double limit locking device for the quick-change demand of batteries in electric vehicles, which achieves quick disassembly and assembly through the linkage of the pressure plate, nut and anti-rotation locking member. Its innovation lies in the combined design of the cross dual-limit structure (the first limit is an anti-loosening groove, and the second limit is an aligned shoulder) and the anti-rotation locking member, which ensures that the battery is solid in the locked state (Figure 2.22). This solution simplifies the operation process but relies on precision mechanical fit and may be sensitive to manufacturing tolerances.

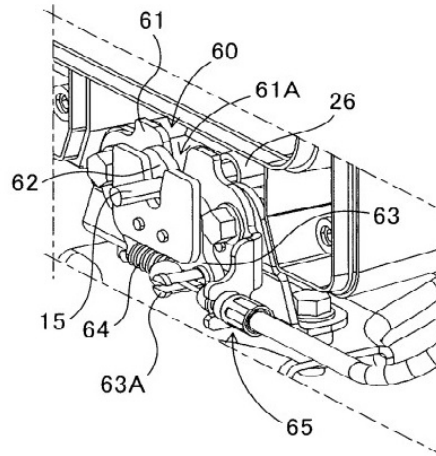


Figure 2.21: Spring loaded battery locking mechanism similar to a car door lock (Source: [34])

CN105150820B [36] and CN109795302B [37], as a divisional application of the same system, jointly construct a linkage locking mechanism. The former achieves rapid unlocking and locking of the battery pack through the synchronized action of multiple locking pins and the linkage bar. The pivoting design of the locking pins allows for efficient operation, while the latter further optimizes the linkage structure by incorporating the locking pin connecting parts into the linkage bar to reduce the risk of external interference and improve unlocking convenience through the split contact block (Fig. 2.23). The interlocking mechanism of the two patents significantly reduces the size and complexity of the locking mechanism and improves the efficiency of power exchange, but it relies on high-strength materials to withstand frequent mechanical movements, and long-term durability needs to be verified.

This chapter focuses on the analysis of existing power exchange technology routes and related patent layouts. It systematically sorts out the current mainstream power exchange solutions and conducts in-depth analysis in multiple dimensions, such as technology implementation, patent protection and market application. By comparing the advantages and disadvantages of different power exchange technology paths, we have clarified the mainstream design ideas and critical technical points in the

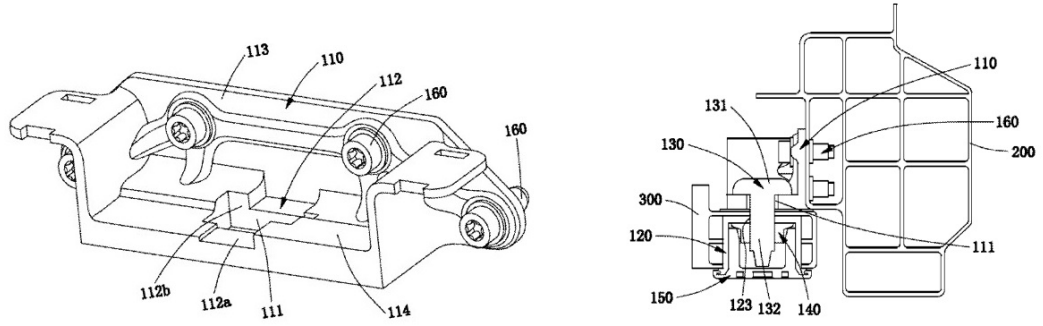


Figure 2.22: Cross double limit locking mechanism (Source: [35])

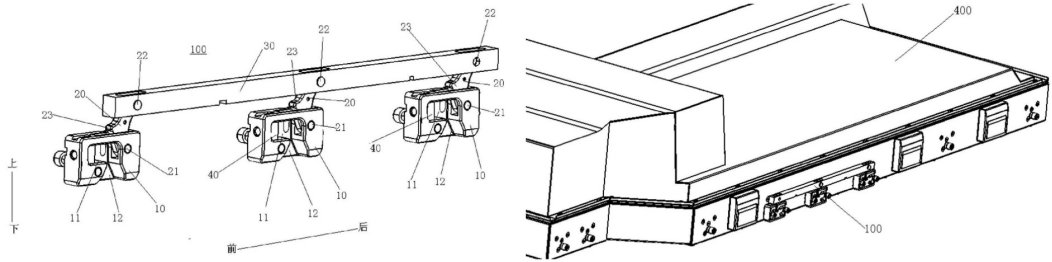


Figure 2.23: Synchronized locking mechanism with multiple locking pins and linkage bars (Source: [36] [37])

industry. These research results not only help us to understand the logic of technical evolution of existing solutions but also provide an important reference basis and innovation direction for subsequent design work.

Chapter 3

Design and analysis of the Power Swap System

This chapter focuses on the design of a battery change system for the Fiat 500e model. Based on the boundaries of the existing body structure, the system is designed to provide certain degree of automation and assist users or workers to manually operate the Trans Pallet to complete the battery swap. The design needs to be optimized within the space of the original battery compartment, considering structural adaptability, ease of operation and system stability, in order to achieve an efficient and safe battery exchange process.

The core of the system lies in the collaborative design of the battery module and the swap equipment, taking into account key technologies such as modular layout, mechanical locking and guided positioning, and verifying its mechanical properties and assembly reliability through structural optimization and simulation. At the same time, the design of Trans Pallet should focus on the lifting mechanism, the fork arm structure and the power exchange method to ensure the precise connection and efficient execution of the power exchange process. The whole system design will be developed and solidified by using SolidWorks 2023 as the design tool, with multiple comparisons, simulation analysis and optimization iterations.

3.1 Conceptual design of the overall architecture of the power exchange system

At the early stage of the design, we conducted feasibility analyses of several possible power swap architectures based on the space dimensions of the Fiat 500e and the existing battery compartment sizes. Considering the 500e's internal and external space arrangement, vehicle dimensions, structural constraints, the requirement for modular split box swapping and protective design of the batteries, we proposed four different swapping paths from Figure 3.1 to 3.4.

From the four sketches, it is easy to see that Figs. 3.1 and 3.2 adopt the bottom

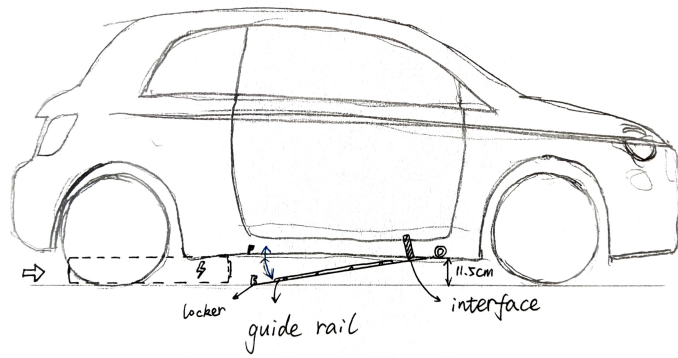


Figure 3.1: Sketch of a power exchange method with a longitudinal slide which can be lifted at the bottom

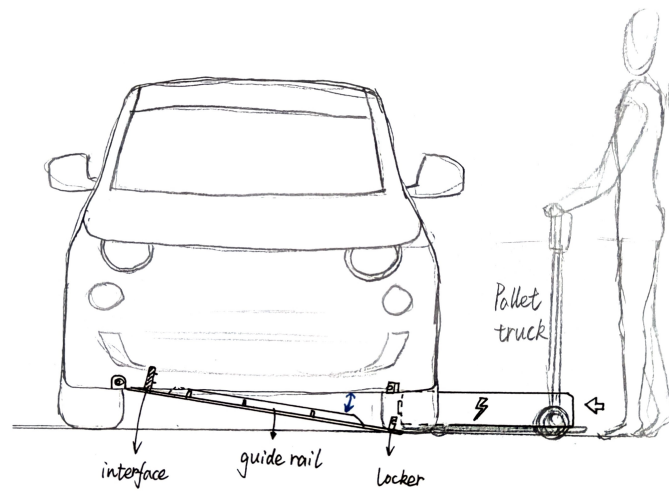


Figure 3.2: Sketch of a power exchange method and equipment with a lateral slide that can be lifted at the bottom

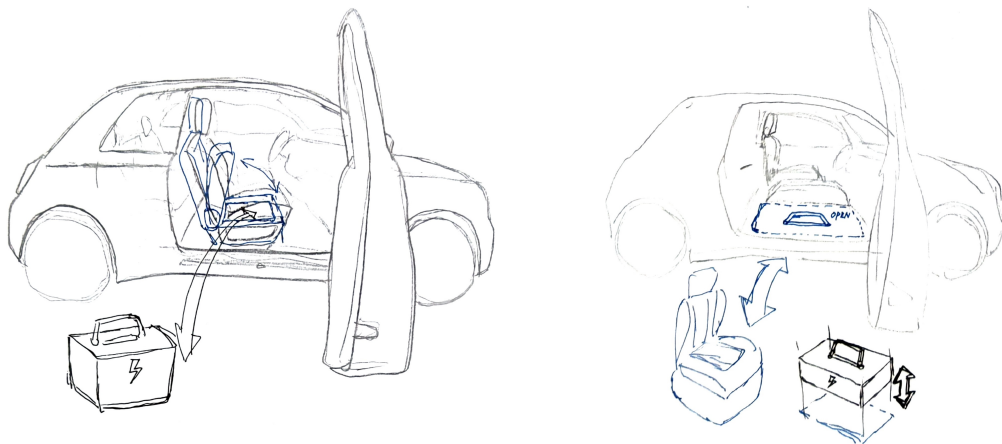


Figure 3.3: Sketch of a power exchange method based on the space under the seat



Figure 3.4: A sketch of a space planning for power exchange based on the space underneath the boot

power exchange method. As design 3.3 and 3.4 need to manually carry the batteries during the swap process, the capacity of a single battery pack is limited, which is not conducive to improving the efficiency of the swap and there is a problem of labor intensity when replacing multiple batteries. Therefore, Designs 3.1 and 3.2 were selected as the initial design direction.

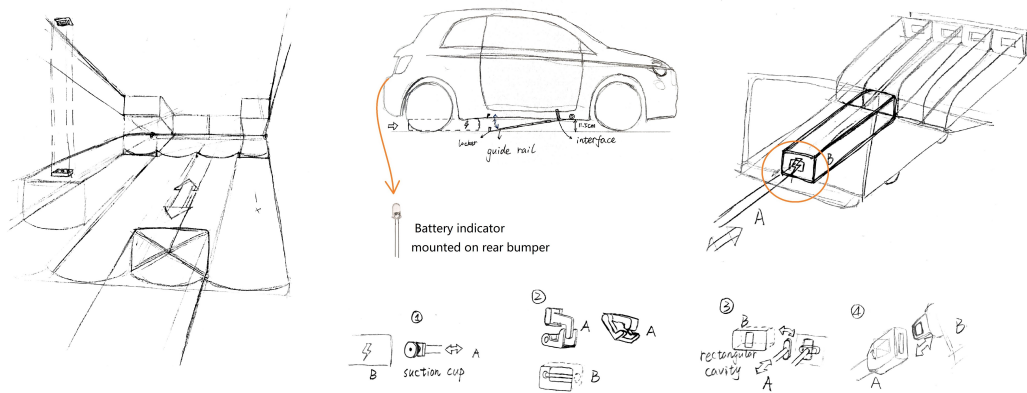


Figure 3.5: Sketch of a further refined design based on the concept of Design 3.1

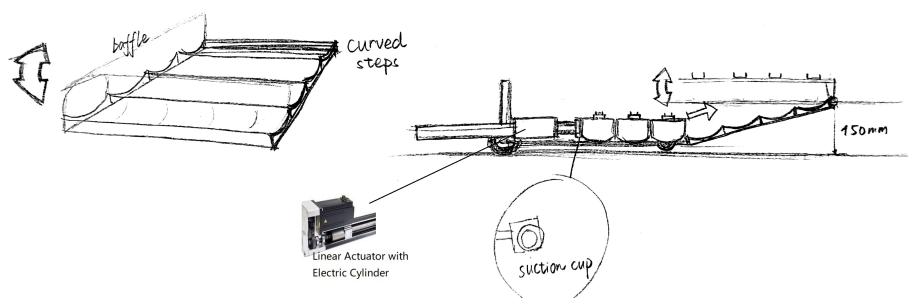


Figure 3.6: Sketch of a further refined design based on the concepts of Design 3.2

As shown in Figures 3.5 and 3.6, we further refined the design based on the previous ideas. We designed a power exchange device with moving wheels and a linear actuator with integrated vacuum suction cups, refined the rails and steps on the battery compartment door to assist in the sliding positioning of the battery, added led indicators to confirm that the battery is in place and to display the power level, explored possible electrical connections between the battery and the vehicle, and a variety of locking mechanisms, and a series of other key performance indicators.

So, based on the design boundary of the existing 500e model, without changing the surrounding beam structure and on the premise of designing within the space of the original battery compartment, the overall architecture of the power exchange system, which consists of exchangeable battery modules and a certain degree of automation of the trans pallet, and where the user manually operates the trans pallet to complete the exchange of the batteries, is basically established.

3.1.1 Design boundaries with data inputs and measurements

The design will be based on the low range battery compartment of Fiat 500e according to the early demand from the company side. Its dimension specification is shown in Figure 3.7.

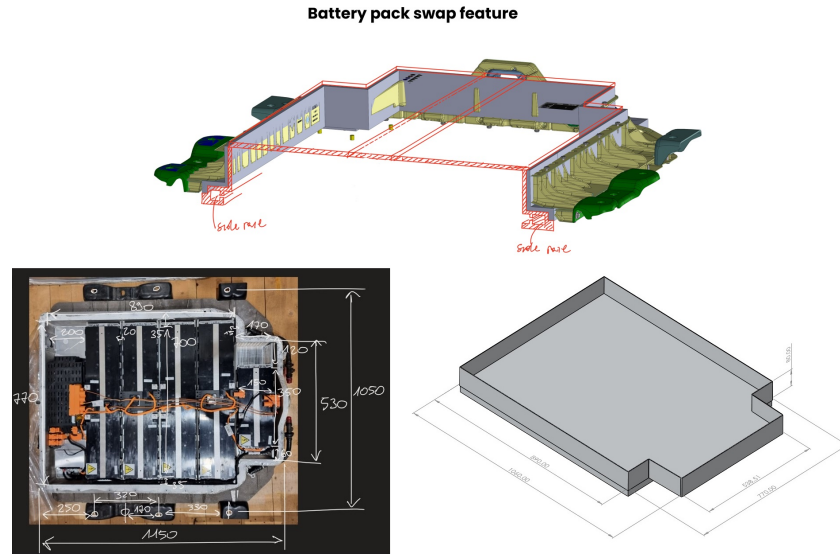


Figure 3.7: Low range battery compartment space dimensions for the Fiat 500e

In addition, there were uncertainties in the current information regarding the actual ground clearance of the vehicle, the space available for the trans pallet to be pushed in, the actual position of the battery compartment on the vehicle and the dimensions of the existing battery modules enclosure, so a number of on-site measurements were carried out to verify each of these (Fig. 3.8). The resulting measurement data served as a supplement to the design boundaries and played an important role in interference detection, scheme optimization and landing of the subsequent design.



Figure 3.8: Double-check measurements of key dimensions

3.2 The battery module design

According to the design ideas in Figures 3.5 and 3.6, we carried out a multidimensional matching design for the battery compartment space and the existing battery pack coldplate casing, combined with the given battery cell specifications. Since there was a variation of battery selection during the project, the design of the module is divided into two phases here: pre and post.

3.2.1 Design of the pre-version battery module

According to the requirements, there should be 28 cells in a battery module in a 14s2p arrangement and a maximum of four modules can be contained in the battery compartment at one time. This 14s2p arrangement comes from the targets we found in terms of C rate charge/ discharge request to the battery in order to perform the WLTC cycle [38] and the prescribed nominal voltage (52 V). The battery cell uses a SAMSUNG SDI model, which we CAD modelled according to its specifications (Figure 3.9).

In order to realise the 14s2p arrangement of the battery cells, we extended the existing coldplate appropriately and experimented with different cell arrangements (Fig. 3.10). Considering the optimisation of the swap process and the safety redundancy of the coldplate, we eliminated the bottom cover of the battery compartment in the subsequent design.

At the same time, we designed an interface with redundant electrical connections (Fig. 3.11). For safety reasons, we arranged the left port in Figure 3.11 on the module side and the right port on the vehicle side, which was replaced by a standardized component at a later stage.

Based on the arrangement of the battery cells, we mapped the bus line corresponding to 14s2p, selected AC-DC converters available on the market to meet the space and performance requirements, considered a simple latch mechanism similar to a door lock (Fig. 3.12), and finally generated two layout ideas (Fig. 3.13 and Fig. 3.14).

1.0.7	Cell Weight (g):	max. 980g
1.0.8	Cell Dimensions, without terminals (mm):	97.67 (H) x 147.74 (W) x 28.32 (T)
1.0.9	Cell Dimensions, with terminals (mm):	101.28 (H) x 147.74 (W) x 28.32(T)
1.0.10	Cell Voltage, nominal (V):	3.67
1.0.11	Minimum Cell Voltage, 25°C (V)	2.80
1.0.12	Maximum Cell Voltage, 25°C (V)	4.25
1.0.13	Capacity, 1C rate, 25°C (Ah):	60 (1/3C rate)

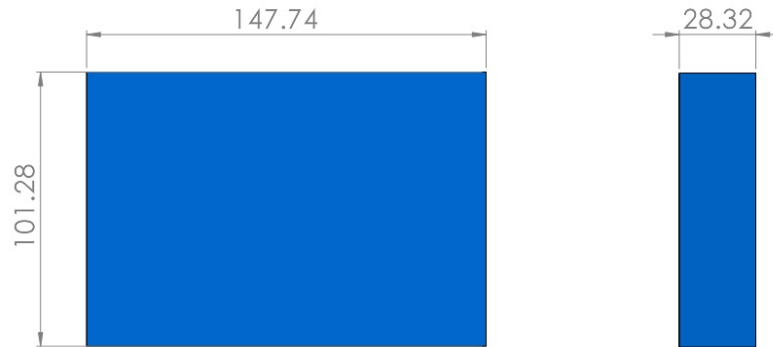


Figure 3.9: SAMSUNG SDI battery cell specifications

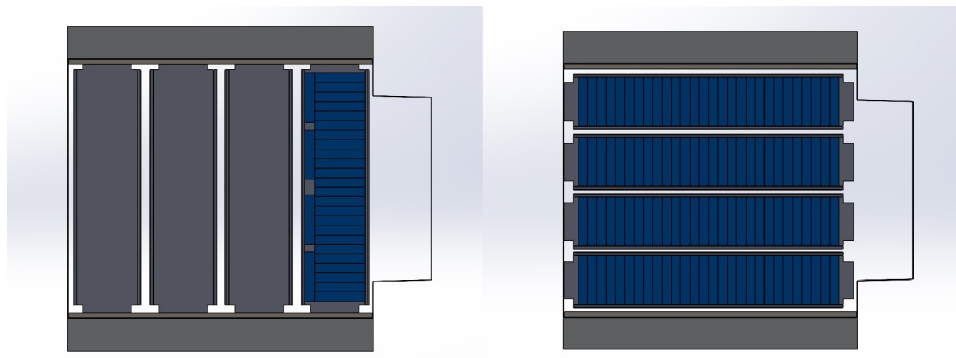


Figure 3.10: Two possible cell arrangement solutions

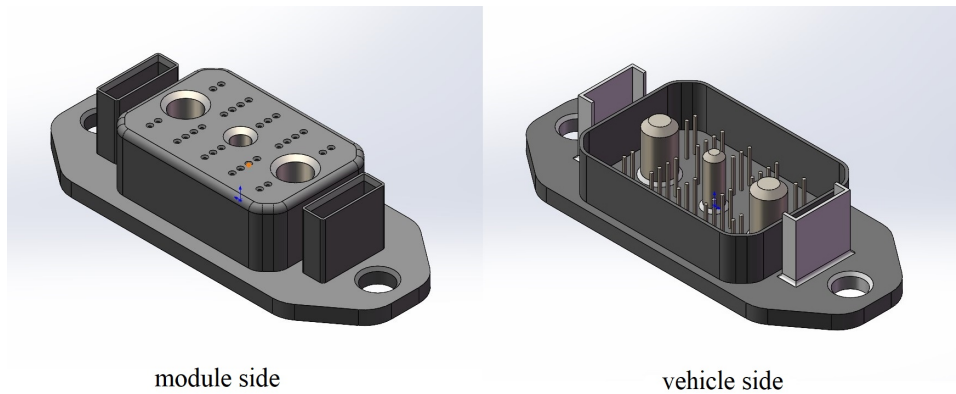


Figure 3.11: Electrical interfaces with redundancy

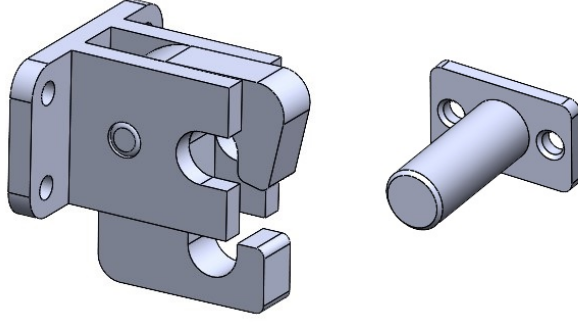


Figure 3.12: A simple module locking mechanism

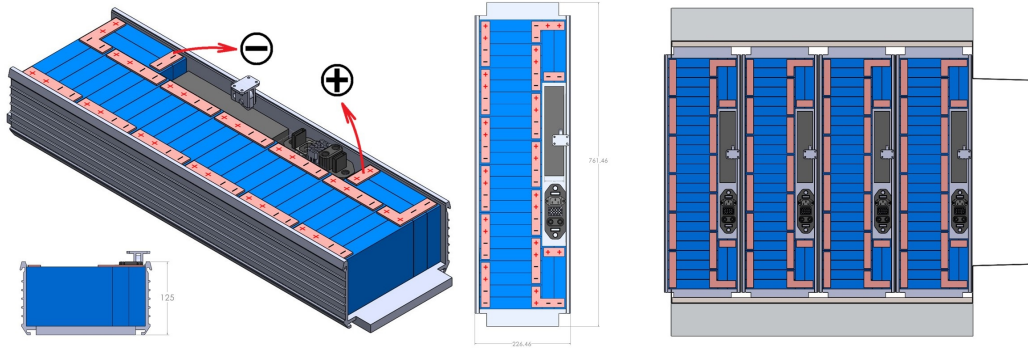


Figure 3.13: Module cell arrangement A

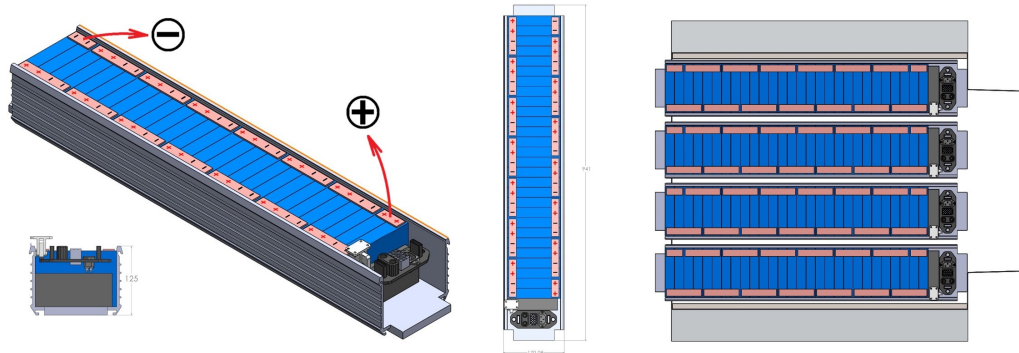


Figure 3.14: Module cell arrangement B

As can be seen from the figures, due to the addition of other components, it is not possible to fit four modules in the low range battery compartment of 500e, no matter if we use A or B solution. After discussing this issue, we decided to abandon the low range battery compartment in favor of a high range (high voltage) battery compartment (Figure 3.15).

The expansion of the space increases the freedom of design and gives us the opportunity to optimize the existing design. In particular, the locking mechanism of the container latch inspired us with its simple structure and excellent reliability, and we tried to design a similar rotational locking mechanism (Fig. 3.16), which connects the coldplate's two side wings with the two longitudinal rails of the compartment

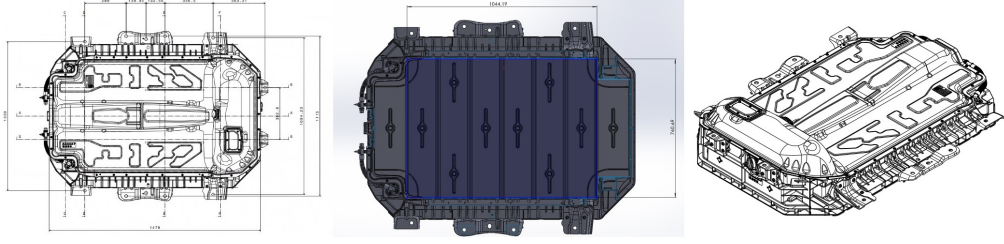


Figure 3.15: Fiat 500e high range (high voltage) battery compartment

for locking (Fig. 3.17).

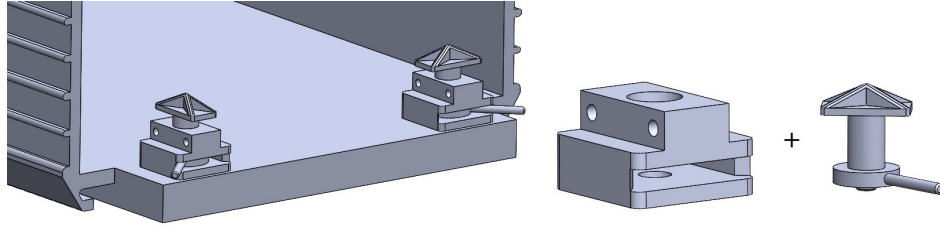


Figure 3.16: A rotational locking mechanism similar to the container latch

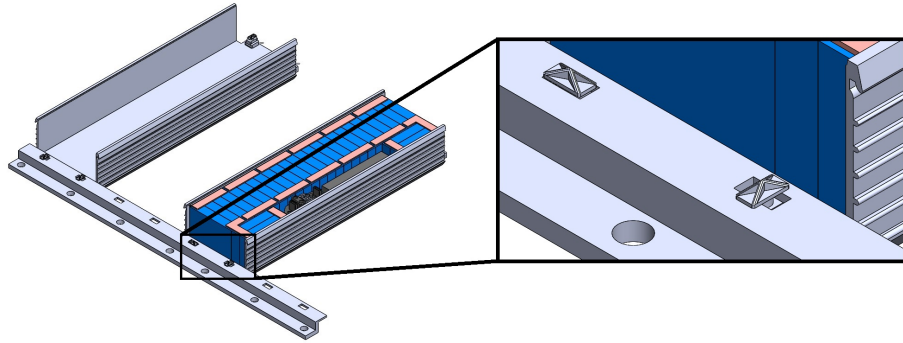


Figure 3.17: Fixing method for connecting the coldplate side wings to the compartment longitudinal rail

Based on this, we roughly estimate the mass of the whole module according to the weight of the battery cell, converter, etc. We calculate the core mass of the module to be 26.804 kg, and take the gravity acceleration into account, the gravity force of the module itself is 263 N. In the figure, we can see that the whole module is maintained by the four rotary locking mechanisms, so in the static simulation, we need to ensure that the four mechanisms are evenly loaded, i.e. each load is 65.67 N. From a conservative point of view, we take the value of 68 N here. In the simulation, 6061 aluminum alloy is used for the coldplate, and Plain Carbon Steel is used for the twist-locking mechanism, we also performed static validation of the coldplate, and the stress and deformation results are shown in Fig. 3.18. The displacement at the maximal point is shown in Fig. 3.18 and the stress at the maximal point is shown in Fig. 3.19. From the simulation results, the displacement order of magnitude at the maximum deformation remains at a low level (1e-03 mm).

Therefore, we believe that the mechanical performance of this structure meets the requirements. However, considering that its rotational locking function is difficult to achieve direct control and execution for the bottom swap method, this combination of fixing method is finally discarded.

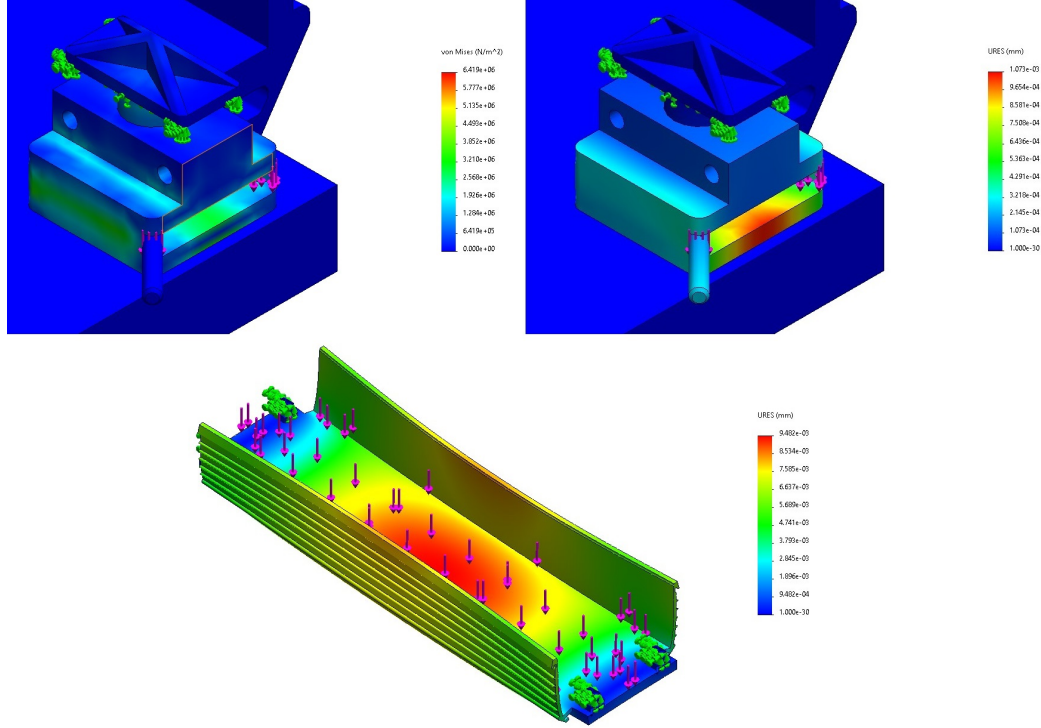


Figure 3.18: Static simulation of rotational locking mechanism

From the point of view of simplification of the locking operation, the design of a door lock mechanism similar to the earlier one returned to our view. After discussion, Stellantis provided a mature door lock system and shared their vision for its application at the module level (Figure 3.19). The system can withstand a maximum of 22,000 N, which is sufficient to withstand the transient load impact of the battery caused by bumps during the vehicle's journey.

Based on the locking mechanism arrangement in Fig. 3.19, we modified the original coldplate by rearranging the original 28 cells and bus lines, created a tilted striker to balance the characteristics of the locking system and the height requirements of the battery compartment, preventing the module from rotating around the axial direction of the striker in the battery compartment, we placed rubber damping parts on both sides of it to improve the stability of the battery fixation. On the vehicle side, we correspondingly designed an S-shaped fixing rail (Fig. 3.20), which is well adapted to the space in the whole battery compartment (Fig. 3.21).

In addition, based on the characteristics of the latch structure, the author proposed a design of a release button based on an elastic reset mechanism, where the pulling motion is converted into a pressing motion by a pulley, and the reset is achieved by a spring (e.g., Fig. 3.22). However, considering the large number of parts and the

- upper door latch with **22000 N** (side right rear door of 500 e)
Part Number serratura ricambi 52211248
Part Number scontrino ricambi 52138463)

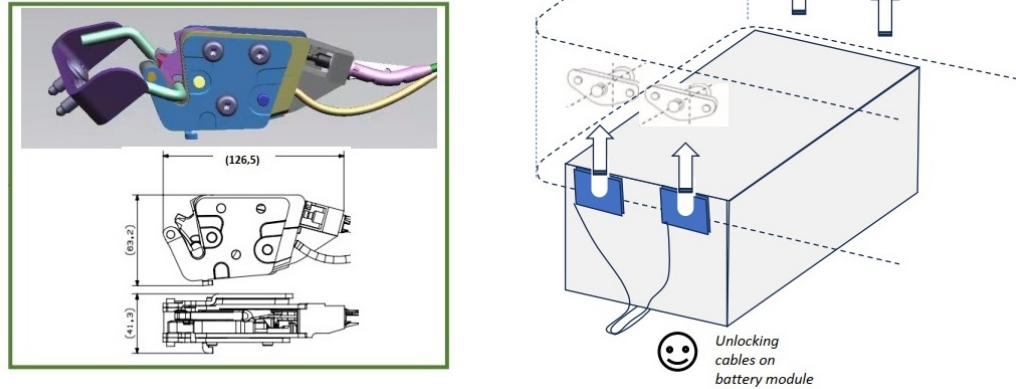


Figure 3.19: Technical parameters of the door locking system and application concepts

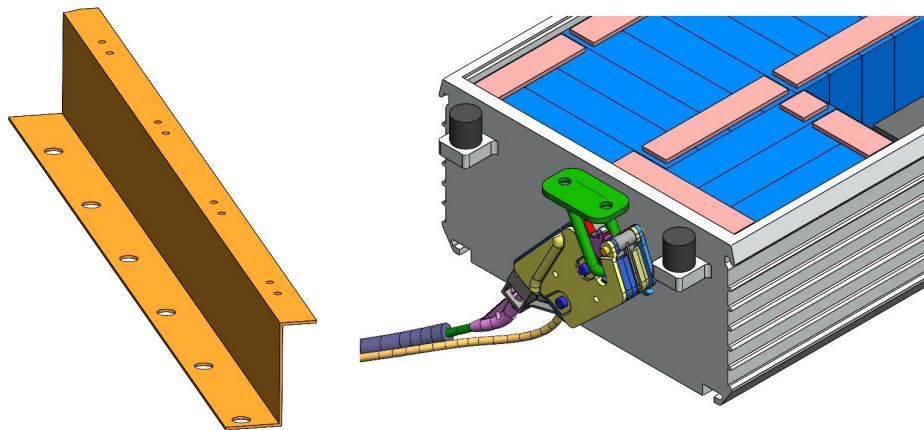


Figure 3.20: Fixing scheme based on door lock system

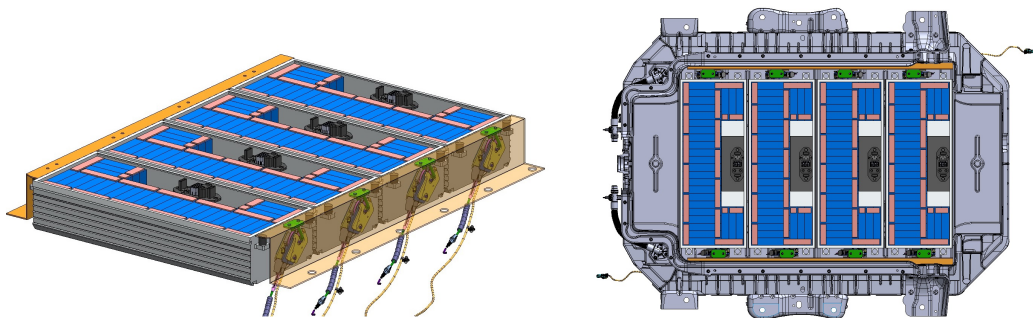


Figure 3.21: Fixed solution in battery compartment

small size of the whole system, the reliability of the structure was challenged, so this design was finally discarded.

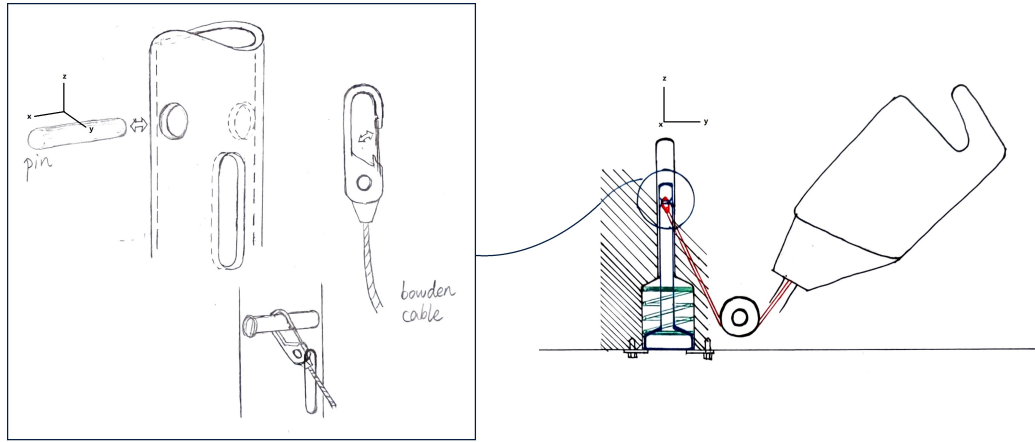


Figure 3.22: A latch press-release mechanism

3.2.2 Design of the post-version battery module

Due to the rapid development and changes in the power exchange industry, the previous power exchange system concept needed to be adjusted accordingly. The earlier four-battery swap solution was also changed to a two-battery swap. The new battery pack capacity and dimensions have been significantly upgraded from the previous version (Fig. 3.23) and the encapsulated battery pack (max. 990 mm * 310 mm * 120 mm) will be supplied directly together with the electrical interface. Obviously, with the size of this battery module, it can only be arranged longitudinally side by side in the battery compartment (Fig. 3.24).

The changed design conditions required a redesign of the holding system. After reviewing the space inside the Fiat 500e's high range battery compartment and the mounting holes for the fixing bolts, we concluded that it would be feasible to adopt a fixing system that would be mounted on both sides of the module in the longitudinal direction.

Similar to the S-beam in Figure 3.20, the S-beam of the new module is designed to consist of a number of aluminum alloy basic components bolted together, taking into account the machining process of the aluminum alloy. Due to the change of mounting position, it is necessary to leave space for the electrical interface and mounting holes for the vehicle side in the top opening of the S beam. In order to facilitate the release operation, we changed the mounting position of the latches from the battery side to the S beam side. This arrangement allows the striker not to need to be tilted as in Fig. 3.20 which reduces the purchase cost.

During the design process, we found that there are four available bolt mounting holes in the battery compartment for fixing the S-beam base plate. For the question

2. Cell Specifications

2.1. Basic Specifications

Items	Standards	Remarks
Capacity (min.)	114.2 Ah	1/3C, 25±2°C, 2.8-4.30V
Energy (min.)	426.0Wh	1/3C, 25±2°C, 2.8-4.30V
Internal Resistance	0.57±0.1mΩ	AC, 1kHz, 30%SOC
Nominal Voltage	3.73V	1/3C, 2.8-4.30V
Cell Weight	1755±30g	
Maximum charging voltage (U_{max})	4.30V	
Minimum discharge voltage (U_{min})	2.8V(>0°C), 2.5V(0°C≤T<-20°C), 2.2V(≤-20°C)	
Charge	Standard Charge Current	1/3C @25°C
Discharge	Standard Discharge Current	1/3C @25°C
Cycling	25°C Standard Cycle	1500 cycle 0.5C/0.5C, 2.8-4.30V, capacity retention≥70%
	35°C Fast Charge Cycle	1500 cycle 4N+2F. See 3.8.3.11, capacity retention≥70%
	35°C Standard Cycle	1500 cycle 0.5C/0.5C, 3.0-4.30V, capacity retention≥70%
Dimensions	Height 1(H)	94.95±0.5mm With terminal. See Figure 1
	Height 2(h)	91.50±0.5mm Without terminal. See Figure 1
	Width (L)	301.8±0.5mm See Figure 1
	Thickness (T)	27.00±0.6mm 30%SOC, the maximum thickness under 300kgf pressure
Energy Density	Mass energy density	≥240Wh/kg
	Volume energy density	≥540Wh/L
Storage Temperature	One Year	0-25°C
	Three Months	0-45°C
	One Month	0-60°C

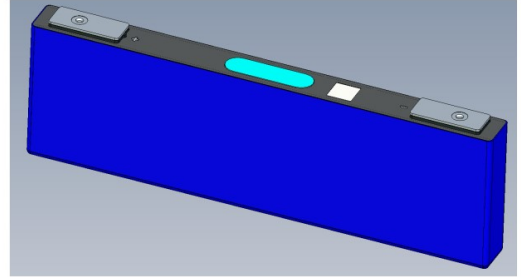


Figure 3.23: Cell parameters for dual-module swapping

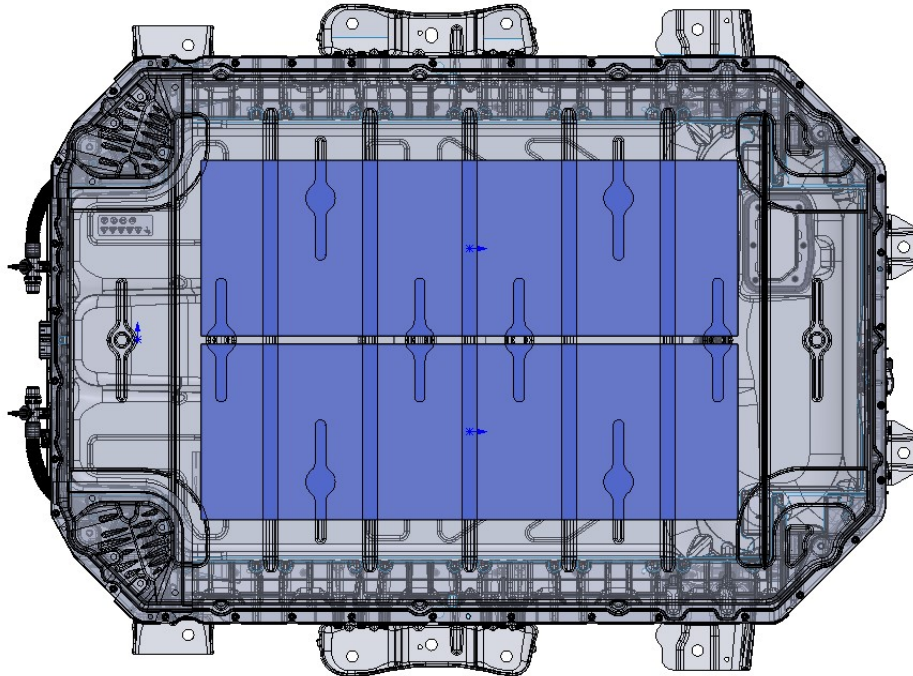


Figure 3.24: Arrangement of two modules in compartment

of whether the S-beam base plate should be fixed by two bolts or four bolts, we used a simplified S-beam to perform a mechanical simulation for the two different ways (Figure 3.25).

In terms of stress, although both solutions exceed the yield limit of the material, it is clear that the 4-hole solution exceeds it to a lesser extent. At the same time, the same trend is observed at the displacement and strain level. The two models used in the simulation are simplified models that are only considered for fast solution, which is convenient for discovering the physical laws of different solutions. The actual products are stronger in terms of wall thickness and structural design.

It can be concluded that for a given load, the 4-hole solution is superior to the 2-hole solution at all stress, displacement and strain levels. Since the S-beam has a significant impact on the installation accuracy of the module, it is necessary to retain the 4-hole fixation to reduce the end displacement.

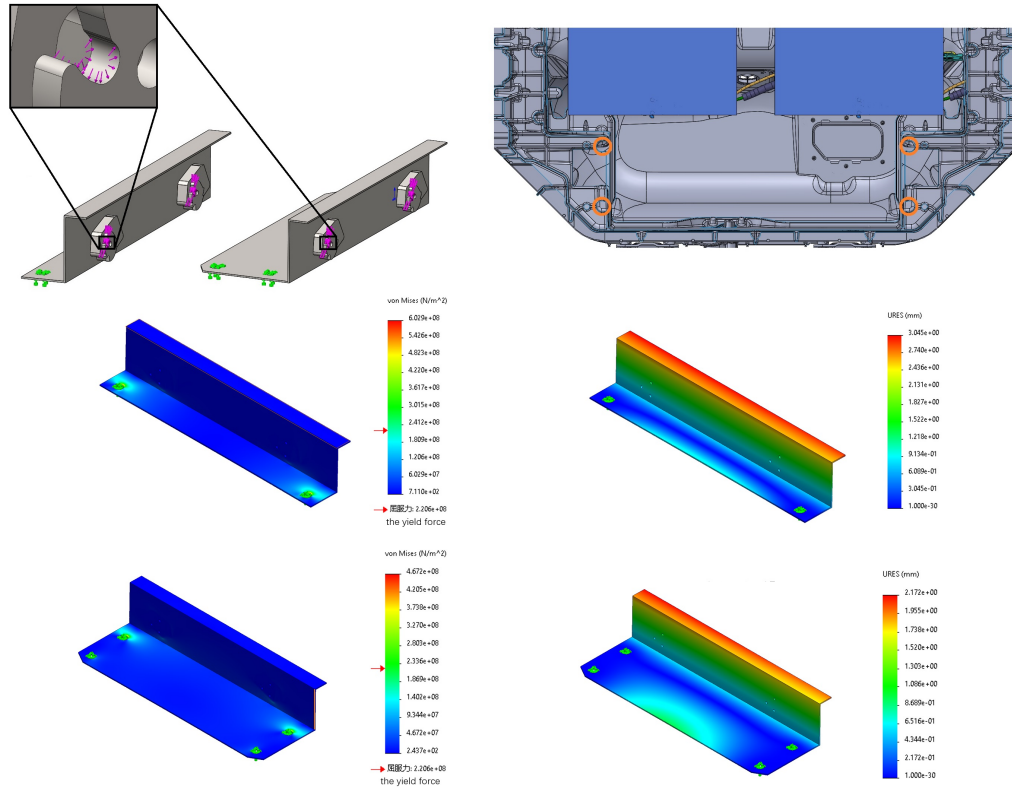


Figure 3.25: S beam base plate with different number of bolts fixing and simulation results

After continuous design-simulation-modification cycles, the final S beam structure was able to control end displacement to less than 0.6 mm under 1.5 times the gravitational load (1764 N) of the battery pack (60 kg mass per module), which is acceptable (Figure 3.26).

In order to verify that the striker can withstand loads consistent with the fixation

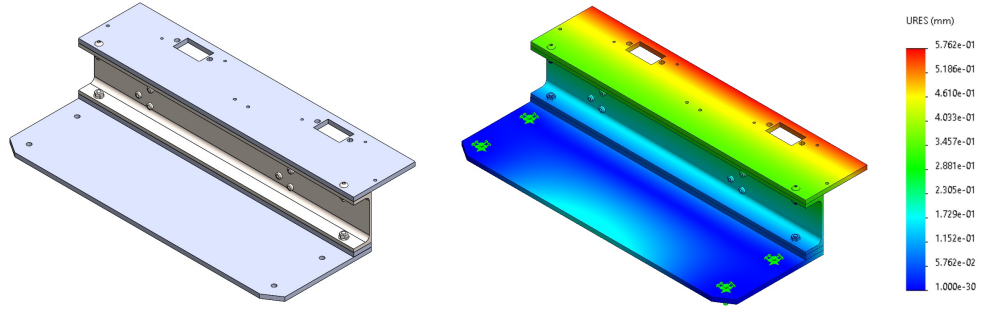


Figure 3.26: Final S beam design and simulation result

strength of the latch, simulations were carried out with a load of 22,500 N based on the parameters of the material provided by the manufacturer (Stricker is steel 38B2 (UNI EN 10263-4) while the base is steel LAH420Y480T) (Figure 3.27). From the results, it is satisfactory.

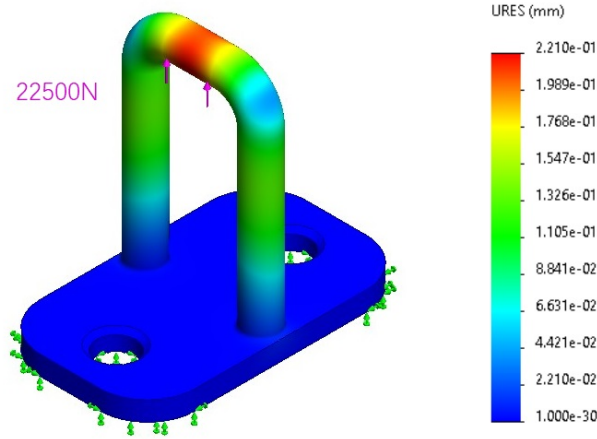


Figure 3.27: Stricker static simulation result

In order to facilitate the positioning in the vertical direction during the exchange process, we designed a guide assembly with a tilt angle and coordination between the vehicle side and the module side. As shown in Fig. 3.28, this design solves the positioning problem well and stabilises the module, while avoiding interference with the latch system control harness.

3.2.3 Battery compartment topology optimization considering power cable

According to the requirements, we also need to design the power cable arrangement connected to the vehicle side port. The technical parameters of the power cable are shown in Fig. 3.29. Following the parameters and bending radius shown in the figure, considering the internal space of the battery compartment, we design the power cable arrangement for the two modules. The scheme shown in Fig. 3.30 is obtained. This scheme meets the needs of all aspects well and avoids the interference

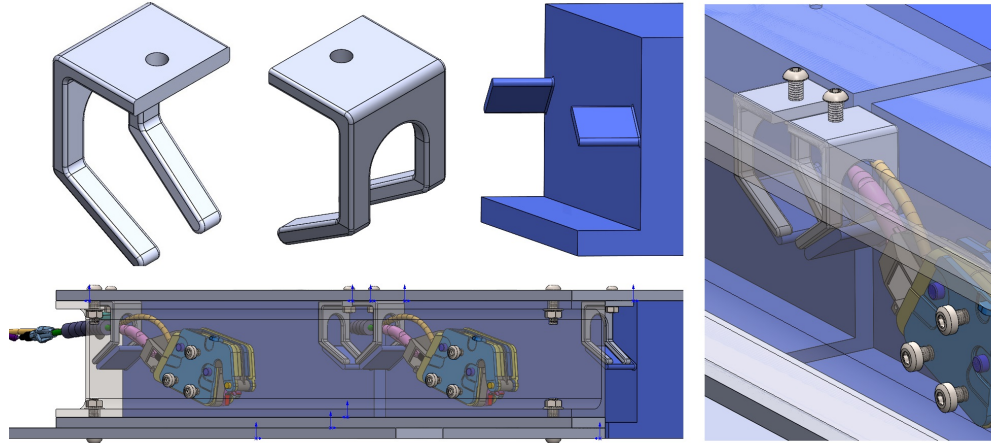


Figure 3.28: Compatible positioning guide components

between the components, which is a more perfect design.

CHARACTERISTICS		DIMENSIONS					
Voltage Rating	0.6/1kV	ELAND PART NO.	NO. OF CORES	NOMINAL CROSS SECTIONAL AREA mm ²	CONDUCTOR DIAMETER mm	INSULATION THICKNESS mm	NOMINAL OVERALL DIAMETER mm
Test Voltage	spark test: 8kV 5 minutes: 5kV	CP101025OR	1	25	7	0.64	12.2
Temperature Rating	Operating temperature: -40°C to +180°C (3000 hours) Short term ageing: +205 °C (240 hours)	CP101035OR	1	35	8.5	0.64	14.4
Minimum Bending Radius	Static installation: 3 x overall diameter Dynamic Installation: 6 x overall diameter	CP101050OR	1	50	10	0.71	15.8
		CP101070OR	1	70	12.5	0.8	18.2
		CP101095OR	1	95	14.8	0.9	20.9
							1150

Figure 3.29: Technical parameters of the power cable

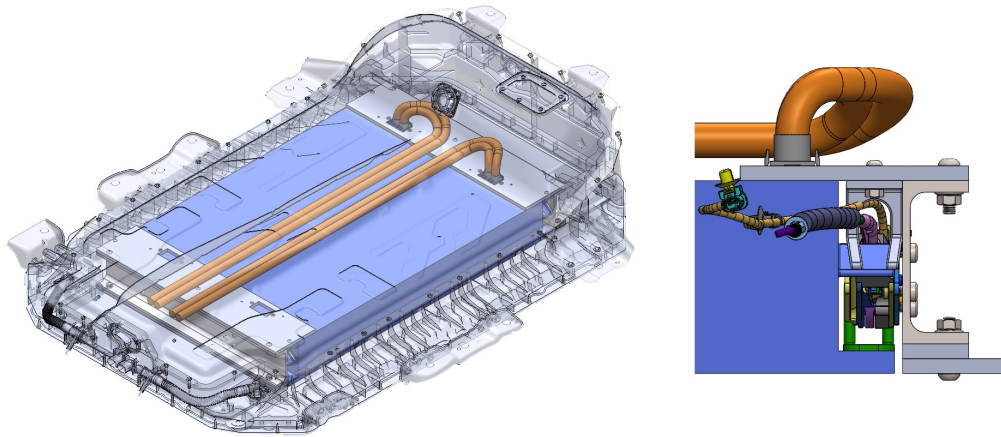


Figure 3.30: Arrangement of the power cable and spatial relationship of the components

3.3 Design of the trans pallet

3.3.1 Concept design and analysis

The conceptual design of the trans pallet was started after the initial design direction of the overall design of the swap system was determined and is closely connected to

the swap method. After obtaining the height of the module (125 mm in the early stage and 119 mm in the later stage) and the ground clearance of the 500e battery compartment (163 mm, see Fig. 3.8), only 38-44 mm were left for the height of the trans pallet, so how to improve the mechanical properties of the structure as much as possible under the premise of spatial constraints became the core issue throughout the whole design.

Inspired by the synchronized lifting and lowering of the far and near ends of a traditional Hand Pallet Truck, the author designed three similar crank-linkage mechanisms (Fig. 3.31), aiming to reduce the end displacement of the fork arm through the support at the far end. However, due to the height limitation, conceptions A and B could not be located at the same height of the rotation axis of the crank before and after the connecting rod, so they could not always be parallel to the ground during the platform lifting process, the module had the risk of slipping, and design C could not lift at a uniform speed due to the structural characteristics of the crank link mechanism which is susceptible to its own mechanical dead spot, the motion transformation at the end of the lifting stroke in the horizontal and vertical directions was gradually retarded, it could not lift at a uniform speed. The diameter of the wheels conforming to the dimensions is too small to meet the requirements of load bearing and possibility. Therefore, none of the three options was adopted.

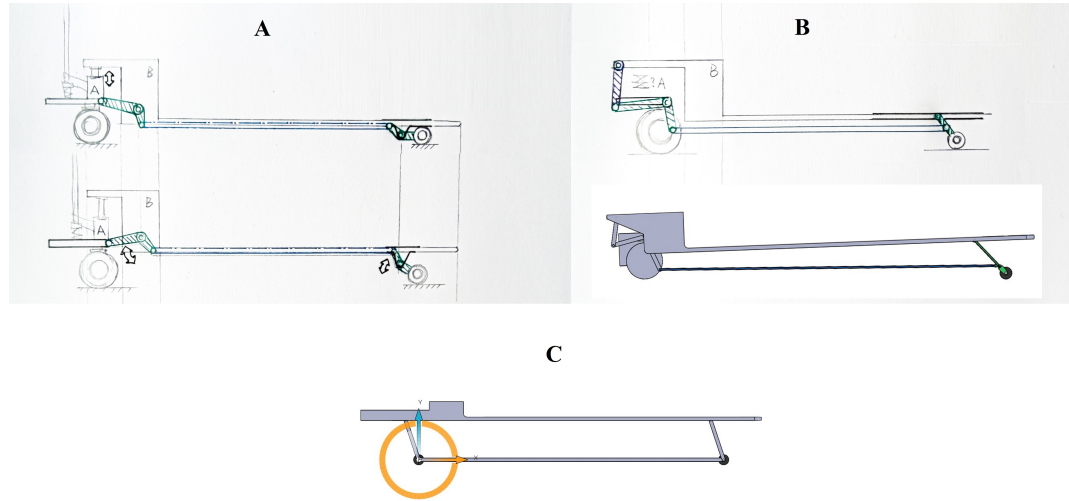


Figure 3.31: Sketch and kinematic validation of three crank linkage mechanism based power exchange lifting devices

After discussion, the design of a set of pallets or fork arms that can be moved up and down along a vertical track, based on the transfer trolley shown in Figure 3.2, became a more achievable solution.

For the transpallet form of the pre-version module, we adopted a longitudinal push-in transpallet from the rear of the vehicle, which reduces the bending moment formed by the module on the fork arm, thus reducing the displacement at the interface. Due to the low volume and mass of the previous version of the module, a narrower

transpallet design consisting of a standard 3030 aluminum profile base and a customized aluminum alloy fork arm was used (Figure 3.32).

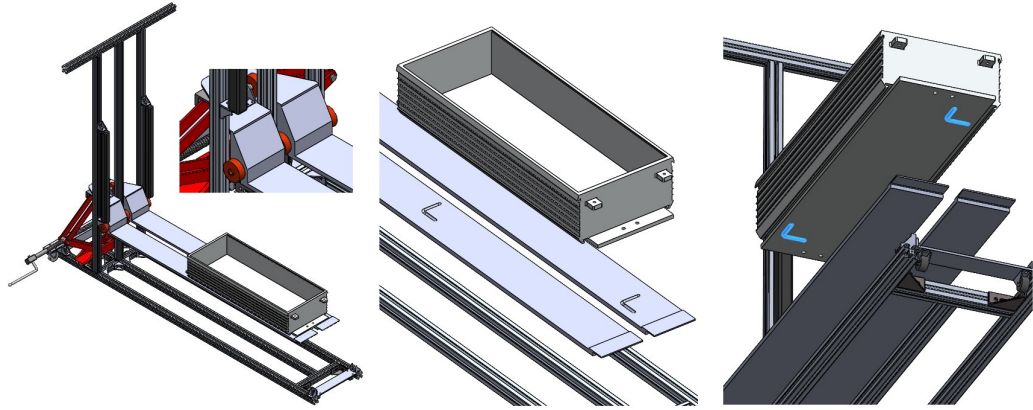


Figure 3.32: Transpallet for the pre-version module

As you can see, the fork arm driven by manual or electric scissor jack slides on the vertical beam through the wheelset, avoiding the wear and tear caused by direct metal contact. In order to ensure the stability of the power change process, we have designed an aligned limit mechanism at the end of the fork arm and the bottom surface of the battery.

For the later version of the module, the battery can only be changed from the side of the vehicle due to a change in the direction of the locking mechanism. For the transversal module, the original transpallet design was too narrow and there was no positioning mechanism in the transversal direction, so there was a risk of the battery slipping out of the device. In order to cope with the above problems, we first considered widening the entire transpallet based on the original design, resulting in the design shown in Figure 3.33. As you can see, the fork arm driven by manual or electric scissor jack slides on the vertical beam through the wheelset, avoiding the wear and tear caused by direct metal contact. In order to ensure the stability of the power change process, we have designed an aligned limit mechanism at the end of the fork arm and the bottom surface of the battery.

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Considering the increase in battery size and mass, we believe that the aluminum profile specification of the previous frame will be difficult to support, which is supported by the fact that in the subsequent mechanical simulation (Figure 3.34), the

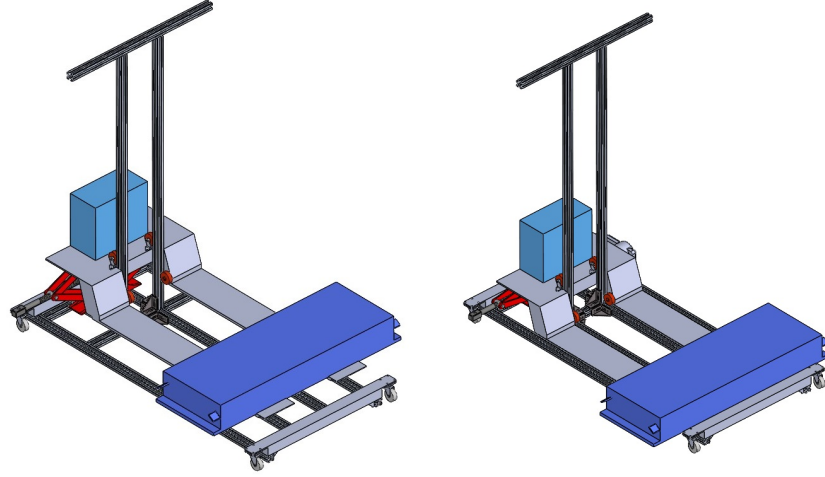


Figure 3.33: Widened transpallet

deformation of the fork arm is too large, resulting in an error that does not satisfy the assumption of small displacements. But this idea of combining the basic frame and the lifting fork arm is still valid, and the subsequent design mainly focuses on structural optimization with the aim of improving the mechanical performance of transpallet.

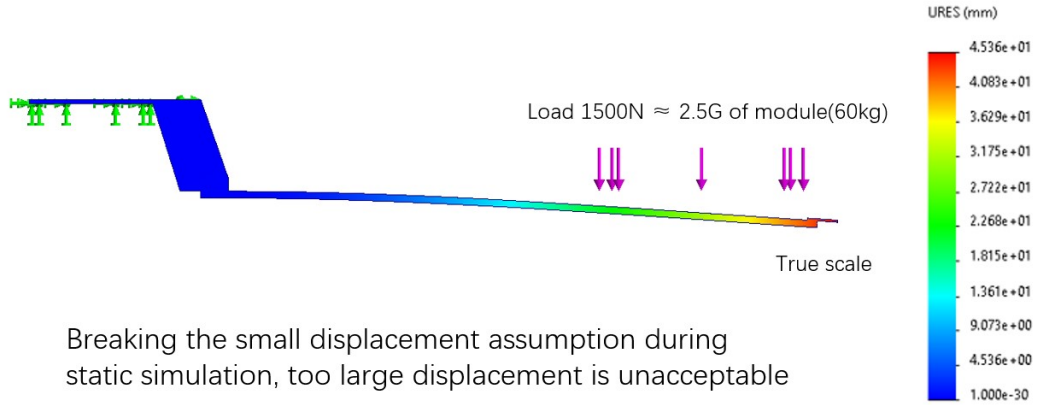


Figure 3.34: Static simulation results of fork arm

3.3.2 Optimized design based on the lift arm structure

Based on the height allowance of 44 mm for the transpallet, the design was developed with the goal of increasing the structural strength of the fork arm. We used more robust profiles and square steel tubes to construct the frame (Figure 3.35), but in the static simulation it can be seen that the end displacement of this design is still too large.

During this period, we conducted a series of experiments using this relatively simplified model to find a more optimal design direction.

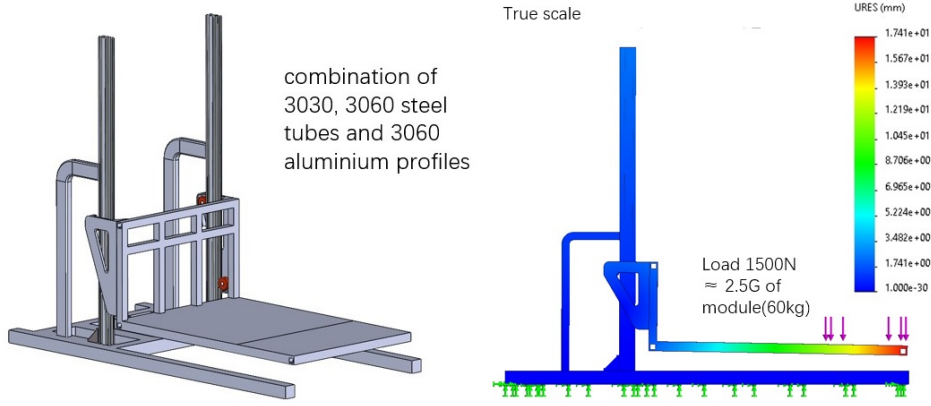


Figure 3.35: Enhanced transpallet framework design and static simulation

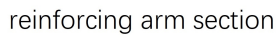
As shown in Fig. 3.36, following the single-variable principle, we conducted several simulations from four perspectives, namely, reinforced structure, vertical distance between sliding wheels, reinforcing arm section at the rear of the transpallet, and different lengths of the vertical part of the L structure, respectively. And repeated each simulation at least three times to ensure the reliability of the results. After analyzing the simulation results one by one, we finally found the best choice of each component of the fork arm as:

- 1.The bottom side of the L-shaped fork arm should use all square tubes.
- 2.The vertical distance between the two wheels of the triangular wheel set should be as long as possible.
- 3.The vertical part of the L-shaped fork arm should be as long as possible.
- 4.3060 steel pipes should be used for the reinforced arms.

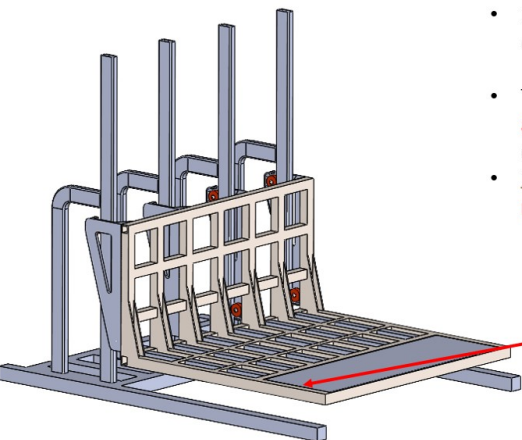
At the same time we realized that, given the current conditions, the end displacement will always exist. So, we designed a rotation mechanism to offset the angular deviation caused by this displacement. Eventually we got the version of the design as shown in Fig. 3.37. As can be seen, a limiting structure was designed to prevent uncontrolled rotation. In this way, combined with the guiding structure in Figure 3.28, the module can automatically align the electrical and fixing interfaces as it rises.

Although the rotating mechanism can better balance the tilt angle generated by the end displacement, its high structural complexity and tendency to stress concentration, which brings increased cost and maintenance difficulties compared to the use of better materials and frame design (the optimized end displacement can already be controlled under 2 mm at 1176 N, i.e. twice the mass load of the module under gravity, generating a tilt angle error of about 0.13° , which is essentially negligible) compares unfavorably with the efficiency ratio and was not kept in the final design.

The frame shown in Figure 3.37, while satisfying the requirement to control end displacement, was more bulky, so simplification of the transpallet while meeting



length of the fork arm's vertical part

- 
- Reinforced fork arm structure based on previous experiments
 - The rotating mechanism requires the entire **fork arm** to be **wider** than the length of the module (936mm)
 - In order to limit the angle of rotation, a **limiting mechanism** has been designed as shown in Fig

44

the mechanical objectives became a subsequent design priority. Based on previous experience, it was felt that increasing the wall thickness of the steel tubes would be a good way to increase the structural strength, but the design could not be divorced from reality and the required tubes had to be able to be produced. In the steel market we found square steel pipes with a specification of 35*35 mm wall thickness of 6 mm and rectangular steel pipes with a wall thickness of 80*50 mm of 8 mm. Using these two sizes of tubes we reconstructed and statically simulated the core of the transpallet. After continuous optimization we obtained the final version as shown in Figure 3.38. After optimization, the end displacement can be controlled to less than 2 mm under a gravity load of 882 N i.e. 1.5 times the mass of the module, which produces a tilt angle error of about 0.13° which is basically negligible, and this is considered to be within the acceptable error range.

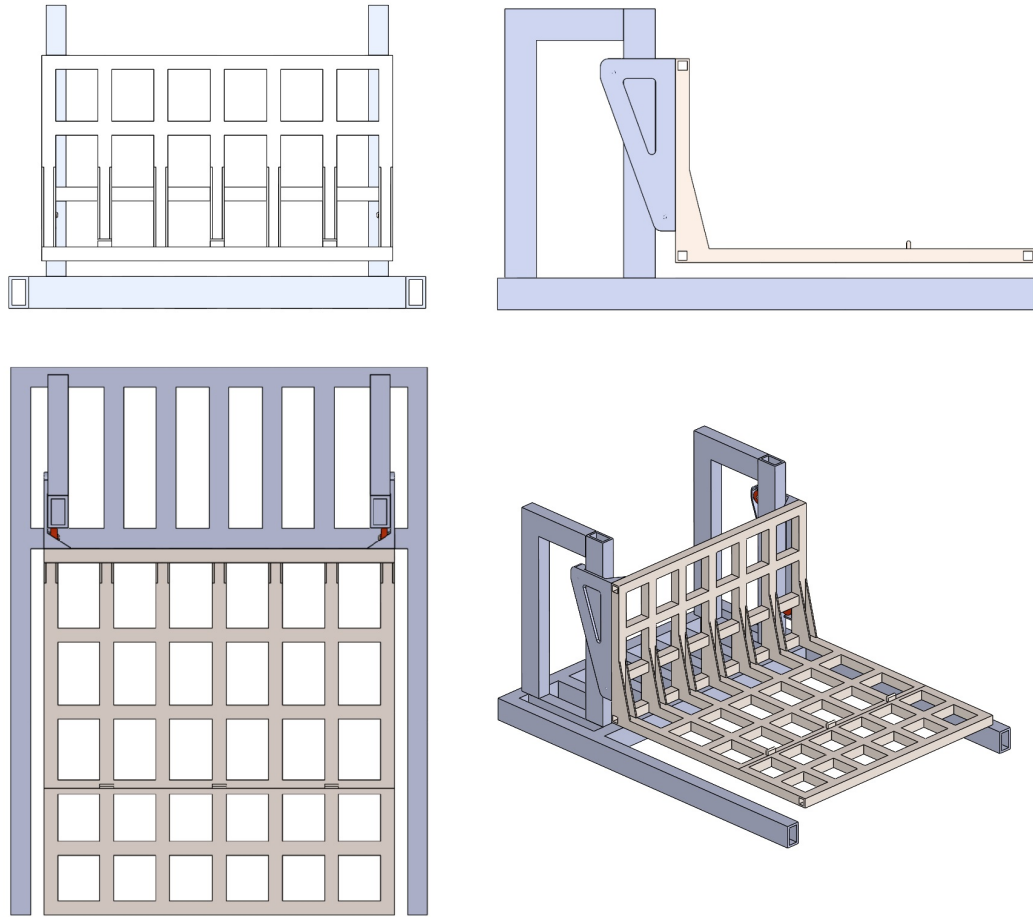


Figure 3.38: Basic framework of transpallet

3.3.3 Selection of lifting mechanism

In order to enhance the automation level of the power exchange equipment, the electric lifting mechanism has become the preferred choice for lifting components due to its advantages of smooth operation, high load carrying capacity, high reliability

and easy control.

As early as the previous design (Fig. 3.32), we chose an electric scissor jack as the lifting mechanism (Fig. 3.39) based on the better load-bearing capacity and lower purchase and maintenance costs. Because its fixed motor rotates at a high speed and has no limiting mechanism, it is difficult to control accurately during transpallet lifting and the mechanism is more exposed, posing a certain safety risk, so we did not choose this mechanism.



Figure 3.39: An electric scissor jack (source: [39])

Screw jacks and linear actuators attracted our attention with their precise movement control and good load carrying capacity. For the two devices, we designed different connection fixing schemes (Figures 3.40 and 3.41). It is easy to see that the linear actuator (6000 N 5 mm/s 12 V) has a more compact size and a more streamlined fixing and connection method than the screw jack, while both can meet the low-speed and large load lifting capacity. At the same time, the packaging is better without the exposure of core components, which reduces the potential safety risks. Based on the above considerations, we finally chose the linear actuator as the core lifting mechanism.

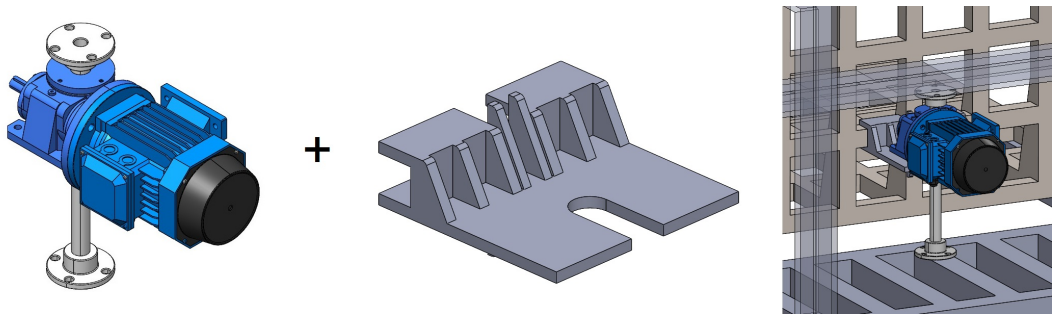


Figure 3.40: Screw jack arrangement and connecting parts

3.3.4 Design of auxiliary positioning device

With both the module connection locking system and the transpallet mobile lifting system gradually improved, how to help users quickly position themselves in the X

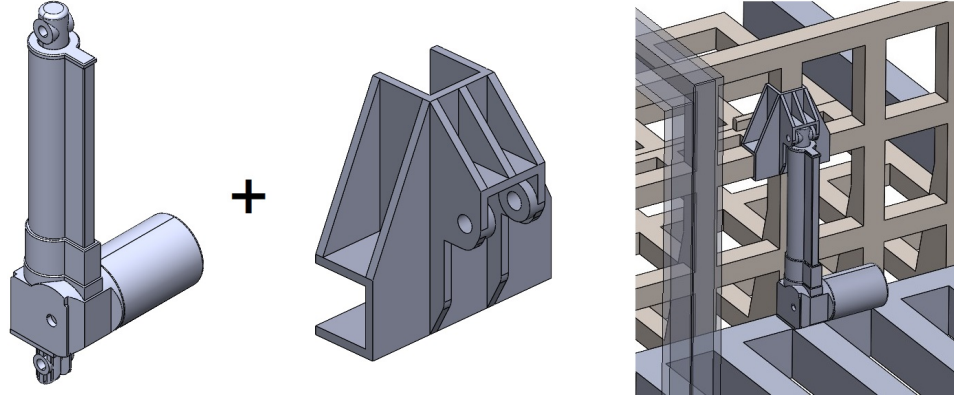


Figure 3.41: Linear actuator arrangement and connecting parts

and Y directions becomes the core problem of the whole power-exchange system.

We first designed a guide rail mounted on the bottom of the vehicle's side beams parallel to the direction of the transpallet's movement, which is pre-positioned by multiple small horizontal pulleys mounted on the upper surface of the module (Fig. 3.42). During the swap, the user needs to raise the module outside the vehicle to a certain height, visually align the top pulleys with the central rail, and then slowly push it in along the rail, with a pair of small stoppers next to the S beam of the battery compartment to assist with positioning. The problem with this design is that the transpallet can only be positioned by the modular 'contact' with the vehicle first, when the user needs to remove the battery, there is no module on the fork arm to achieve positioning. Therefore, this solution was discarded.

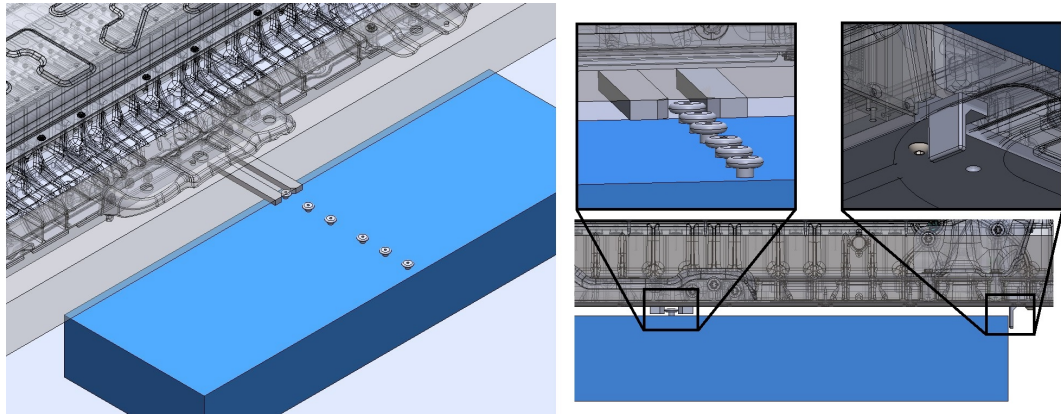


Figure 3.42: Positioning system consisting of module top surface pulley and side beam slides

Considering that the positioning problem cannot use the module as a media, we designed a sloping block that gradually shrinks from outside to inside on the bottom surface of the vehicle, together with the sliding head fixed by the transpallet to realize the automatic positioning when the user pushes in (Figure 3.43). This design avoids the need for the user to visually control the height in the previous design through the

heightened arrangement of the contact body, simplifying the swap process. However, since the tilting block needs to occupy a large space in the XY plane under the vehicle, its arrangement is bound to interfere with the vehicle's suspension and other structures. Therefore, this positioning system cannot be realized.

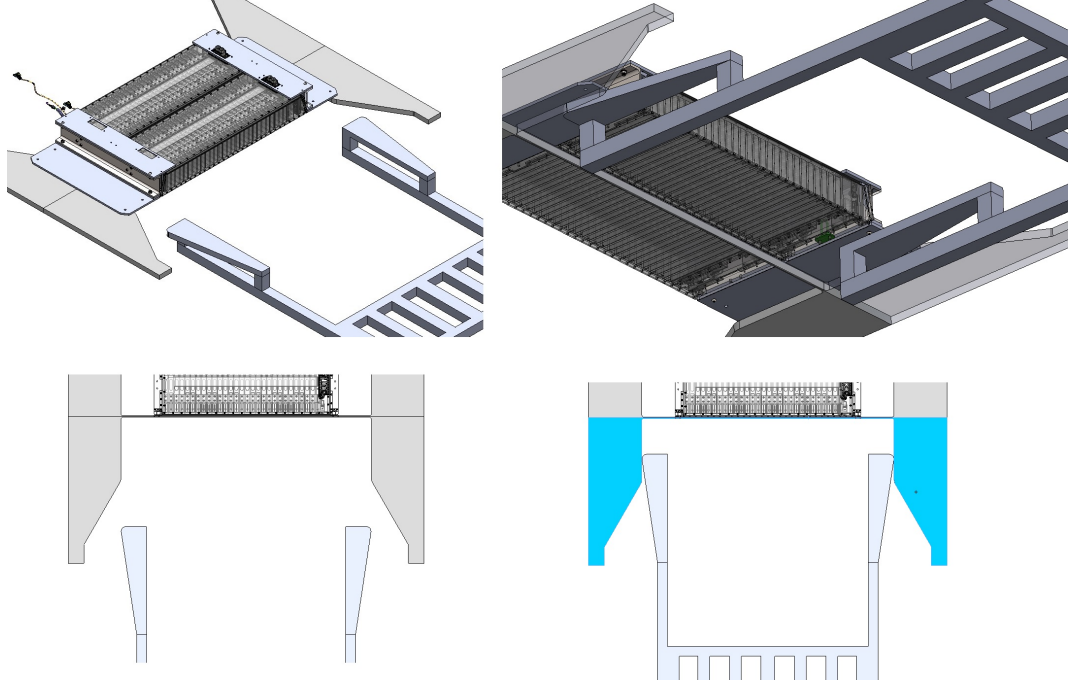


Figure 3.43: Positioning by sloping block and sliding head contact

Based on the experience of the previous design, we decided to consider both the module and the transpallet, designing a positioning system that consists of the vehicle side beam guide A, guide B mounted on the bottom surface of the S beam, the central stopper C, and the no-load guide block D on the transpallet (Figure 3.44).

During power swapping, the user first aligns guide rail A on both sides of the module, slowly push it in, and guide rail B will be on the outside to ensure precise positioning. When unloaded, the user pushes the transpallet so that the guide block D is between rails A and B. After raising the fork arm, the user slowly pushes it in the y-direction until the fork arm touches the intermediate block C to complete the positioning. The system smartly avoids interference between the components and allows precise positioning of the transpallet in multiple dimensions, while being easy to operate and without the need for excessive operation.

So far, we have obtained a relatively complete power swap system (Fig. 3.45), which basically achieves the design goal of ‘based on the design boundary of the existing Fiat 500e, without changing the surrounding beam structure and within the space of the original battery compartment, design a system consisting of exchangeable battery modules and a certain degree of automation of the trans pallet’.

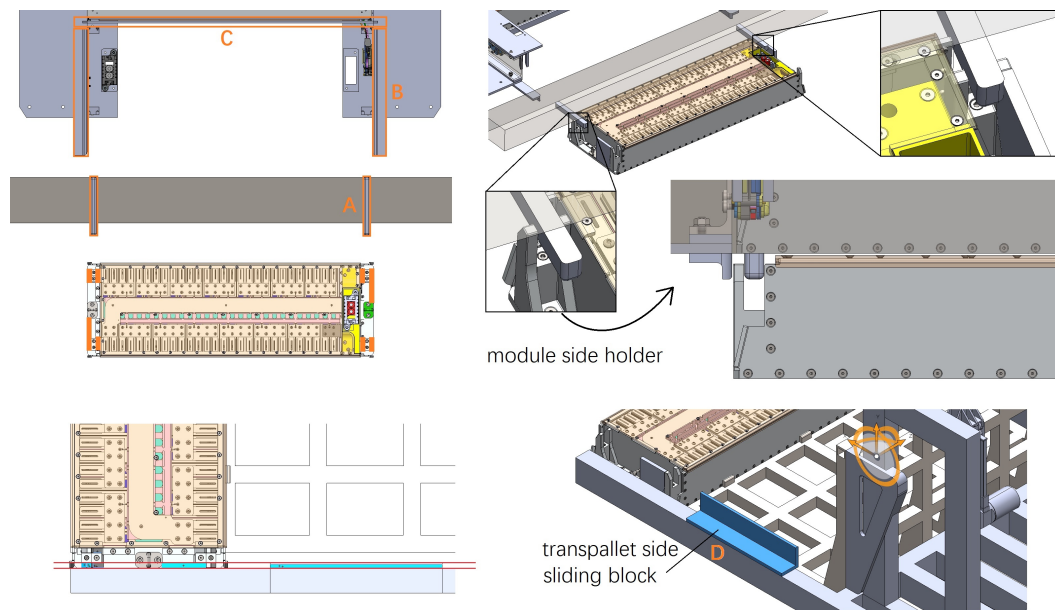


Figure 3.44: Distributed Multi-Rail Positioning System

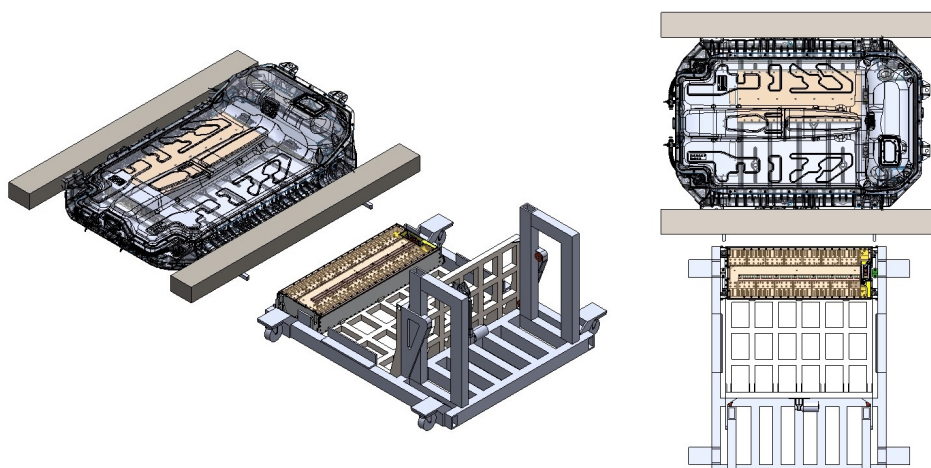


Figure 3.45: Power swap system suitable for Fiat 500e

Chapter 4

Analysis and Comments: Future Developments and Final Remarks

4.1 Improvements and Future Works

Based on the trial production results, the initial functional requirements and design vision have been largely realised. The specially designed battery compartment can be guided to achieve physical and electrical connections or release from the vehicle while still meeting the required capacity cell capacity and structural strength.

Although the current design largely meets initial requirements, several improvements are needed. For instance, the existing transpallet’s ground clearance of only 7 millimeters results in unsatisfactory pass-through performance, which requires ongoing improvement. Furthermore, considering the vehicle connectors will be exposed to the air when the battery module is not mounted, the waterproof and dustproof design of the connection structure should be further optimised while minimising installation resistance and lightweighting. Concurrently, the topology design of the Switch box within the battery swapping system—comprising the BMS, conductors, and power supply cables—will undergo continuous refinement towards low cost, lightweight construction, and high maintainability. Furthermore, the design of the module release control system and the in-vehicle user interface will be further developed in future work.

4.2 Final Remarks

Overall, after a year of systematic design, iteration, and optimisation, we affirm both the technical approach and engineering outcomes presented in this thesis. This project adopted a design process centred on digital twins, enabling a highly digitalised and data-driven approach throughout the entire cycle—from solution conception and selection to structural design and performance evaluation. Compared to

the traditional ‘prototype-testing-rework’ approach, this methodology significantly enhances development efficiency, reduces time and costs associated with physical prototyping and testing, and enables critical design decisions to be validated at an earlier stage.

However, it must be noted that the current achievements remain primarily validated within simulation environments, representing an earlier phase within the engineering realisation pathway. While digital twin models can to some extent replicate the mechanical behaviour and operational characteristics of real systems, the models themselves are unavoidably constrained by assumptions, boundary conditions, and parameter accuracy. Consequently, although simulation validation provides robust theoretical support for design, its outcomes require further confirmation through subsequent physical prototype manufacturing, experimental testing, and real-vehicle integration validation.

From an engineering development viewpoint, this research establishes a robust foundation for subsequent prototype development, but still requires substantial effort to bridge the gap from simulation to reality. Future work should focus on advancing model accuracy, supplementing boundary conditions, conducting experimental data back-alignment, and enhancing hardware integration. This will ensure the digital twin design achieves genuine engineering feasibility and industrial realisation value.

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