ROMO – *THE ROBOTIC ELECTRIC VEHICLE*

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Abstract

This paper outlines the development of the ROboMObil, an innovative electro-mobility concept based on intelligent central control of four *Wheel Robots*, which integrate the drivetrain, brakes, steering and dampers. The motivation behind the *Wheel Robot* concept, the implementation details together with the suspension design are described. The electric power system, consisting of a Li-Ion battery cluster to provide high-voltage power for propulsion and a low-voltage supply for vehicle control, is also discussed. Finally, we provide an overview of the Shared Autonomy control architecture and an outlook on the future research projects based on this demonstrator platform.

1. INTRODUCTION

The ROboMObil is an electro-mobility concept based on intelligent central control of four *Wheel Robots*, which integrate the drivetrain, brakes, steering and dampers. The integration of the vehicle dynamic actuation systems in the wheel vicinity is a relatively new development, and in recent years, several concepts and prototypes of this idea have emerged. Examples include the Michelin Active Wheel [1], Siemens VDO eCorner [2], MIT Wheel Robot [3], Volvo ACM [4] and the Nissan Metamo system [5]. In the case of Michelin, full size electrically powered vehicle prototypes (Heuliez Will and Venturi Volage) with the integrated wheel unit have been demonstrated [6]. Some developments focussed on imparting the vehicle with the ability to rotate about its central axis or even to drive sideways, requiring extended steering angle ranges on all four wheels (e.g. Toyota Fine-X, Nissan Pivo II, MIT prototype with its *Wheel Robot* 5). This requirement of the extended steering angle on driven wheels necessitates the use of wheel-mounted drive systems and a certain degree of system integration into the wheel envelop. The ROboMObil makes use of the enhanced manoeuvrability offered by high steering angle range and in-wheel drive motors in the context of an autonomy-capable prototype vehicle.

Being a clean-sheet design, the ROMO explores the possibilities available for the future of mobility without the constraints applied by the modification of a conventional vehicle, making use of developments in intelligent systems from the field of robotics. With four mechanically independent modules, the ROMO allows the possibility of modifications to the chassis without affecting the powertrain, which is located completely in the two axle modules, with the actuators fully integrated within the *Wheel Robots*. The other modules are the body, which forms the structure of the vehicle and carries the cockpit, and the battery mounted beneath the cockpit floor. An intelligent robot control concept provides the ROMO with enhanced manoeuvrability.

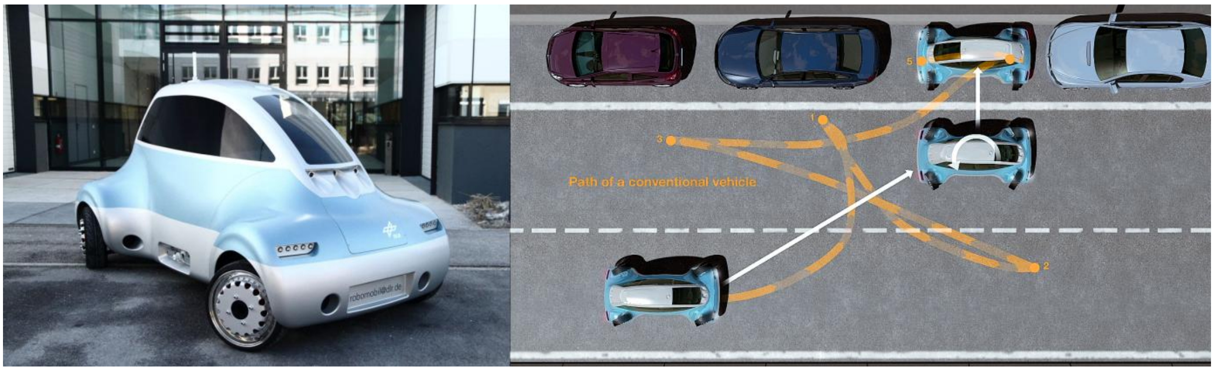

Figure 1: ROMO (left); simplified parking through higher manoeuvrability (right)

The driver input can be given using a side-stick either from within the vehicle or via remote control. With the help of the integrated surround video cameras, the ROMO can be driven with various degrees of autonomy, from partial to fully autonomous. The modular design comprising the front and rear chassis modules, battery module and body module with cockpit makes ROMO an ideal technology platform for innovative vehicle dynamics control and energy management research, and a demonstrator for the fusion of robotics and electro-mobility.

With energy efficiency becoming increasingly critical in all forms of future mobility, much attention has been paid to the energy supply of the ROMO. As well as employing state of the art Li-Ion battery technology, much effort is being put into modelling and estimation of the behaviour of the batteries. This paper is organised as follows: A more detailed description of the *Wheel Robots* is given in Section 2. The model-based development of the suspension is closely related to the *Wheel Robot* concept and is described in Section 3. The electrical system and the initial developments of the battery state estimation algorithms are described in Section 4. Finally, a brief overview of the control architecture is given in Section 5, followed by concluding remarks and an overview of the current research topics in the ROMO project in Section 6.

2. INTELLIGENT ACTUATOR CONCEPT – THE WHEEL ROBOT

The concept of *Wheel Robots* is derived from robotics and Mars rovers [7], with all the actuators integrated in-wheel. Each actuator is controlled by a separate local control unit, with a central control computer communicating with these units to coordinate the vehicle's motion. Together with the integrated in-wheel steering mechanism and in-hub traction motors, an extended steering angle of 95° to -25° degrees is realised. As a result, the ROMO is able to rotate around its own vertical axis (centrically and eccentrically) and move sideways. Such a degree of steering freedom would be difficult to achieve with a chassis mounted drive motor and drive shafts. With the independent control of four wheel-steering actuators, four electric wheel hub motors and two friction brake actuators (each actuating two callipers), the vehicle dynamics variables of yaw rate, side slip angle and vehicle velocity can be decoupled and independently controlled. These four *Wheel Robots* are integrated in two axle modules, which have identical electrical systems of drive inverters, backup batteries and step down converters. The *Wheel Robot* design and their integration into the vehicle are shown in Figure 2.

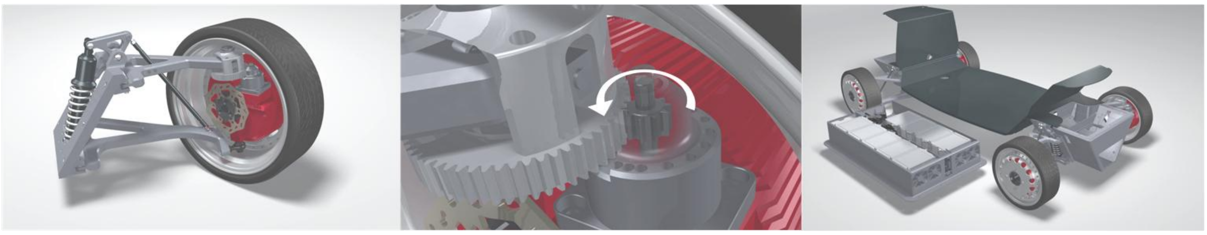

Figure 2: The Wheel Robot with the in-wheel actuators and suspension (left); steering mechanism (middle); module concept (right)

The permanent magnet synchronous motor (PMSM) in-wheel traction architecture provides a nominal rate of 1000 rpm without field weakening, which corresponds to the design maximum vehicle velocity of 100 km/h with the fitted 17" wheels. Each motor can deliver a peak torque of 160 Nm. The motors have an air-cooled inner-rotor design, with the aluminium stator housing also acting as a heat sink. Analyses have shown air-cooling to be sufficient at these power levels, and it leads to a significantly simpler and lighter design compared to liquid-cooling. The stator housing also plays the role of wheel carrier with its connections to the ball joints at the end of the upper and lower wishbones.

The individual wheel steering consists of a rotary electric actuator mounted on the traction motor housing (see Figure 2-middle). The pinion gear on the actuator output rotates around a larger gearwheel, which is rotationally constrained to the upper wishbone while remaining coaxial with the king pin axis. Compared to steering actuation via a tie-rod, this direct rotational actuation of the steering axis allows a very large steering angle range limited only by the physical clashing between the wheel and the wishbone. This rotational constraint on the large gear wheel presents a mechanical challenge as it must be effectively connected to the upper wishbone via a Cardan joint. This is solved by the use of the novel "sliding-block" mechanism (see Figure 2 middle).

The steering actuator uses a 370W brushless DC motor with a harmonic drive CSG series gear component set. The system is specified to achieve similar road wheel steering speeds to that of a human driver in extreme situations, which is accepted to be approximately 80°/s. This corresponds to 1200°/s at the steering wheel for a sporty steering ratio of 15:1, well above the 500°/s specified in test procedures [8] and the 1000°/s used in industry circles. For the control of the steering angle two angle sensors are used. The first, a resolver, is used to measure the rotation between upper wishbone and the wheel carrier. The other sensor is located at the electric drive side and is also used for field oriented control of the motor. The use of the second wheel mounted resolver compensates motor oscillations due to elasticity in gears and guaranties stationary exactness.

The friction disc brakes are Magura hydraulic fixed calliper units for go-karts, selected as they have a similar weight per brake ratio as the ROMO. The master cylinder is driven by an electromechanical linear actuator comprising a spindle drive and a PMSM motor. This system allows braking with a deceleration of 8.8 m/s^2, exceeding the ECE R13 service braking requirement of 6.4 m/s^2. A friction brake system, lockable via a spiral spring mechanism and powered by redundant LV batteries, is necessary on the ROMO for three main reasons:

- To provide a parking brake function, and to hold the vehicle on an incline
- To provide an emergency brake system in case of loss of the HV power supply
- To assist the traction motors working in generator mode to provide a higher deceleration potential

Currently, concepts are being studied to optimise the cooperative braking function between the traction motors and the friction brakes. Upcoming and progressing development work on the *Wheel Robots* include the thermal modelling of the air cooled traction motors and the identification of the steering system on a test bench.

3. SUSPENSION DESIGN FOR WHEEL ROBOTS

The demanding requirements of the wheel rotating a minimum of 90° in one direction, yet also support a 900 kg total mass in maximum lateral accelerations of 1g presented a challenge for the suspension design. The considerations of stiffness, simplicity for prototyping and availability of proven design methods for high load vehicle dynamics led to a design based on a conventional double wishbone layout. Other designs with movable linkages or top-hinged wheel carriers (similar to a shopping trolley) [5] suffer from high complexity, significant design effort and stiffness issues, which could not be overcome within the scope of this project.

The high operating speed of up to 100 km/h imposes the usual automotive requirements on steering axis design, such that the wheels are self-stabilizing in the absence of steering actuator moment. In short, this demands a positive trail value. The scrub radius is set to a minimum value to minimize steering torque due to acceleration and deceleration, thereby reducing the loads on the steering actuators. The in-wheel traction motor design offers advantages in anti-dive and anti-squat due to the same moment arm for both drive and braking. Some suspension parameters can be found in Table 1.

In terms of mechanical component design, the large steering angle range demands shaped, slender wishbones (see Figure 3-left). Since this wishbone also had to carry the steering moments (the steering actuator lies on the wheel end of the wishbone), the loads led to a challenging task for the design team. An analysis with modelling of the wishbones as flexible bodies using Modelica demonstrated the sufficient stiffness and strength of the design in a vehicle driving simulation, with the deflections having minimal effects on vehicle behaviour [9].

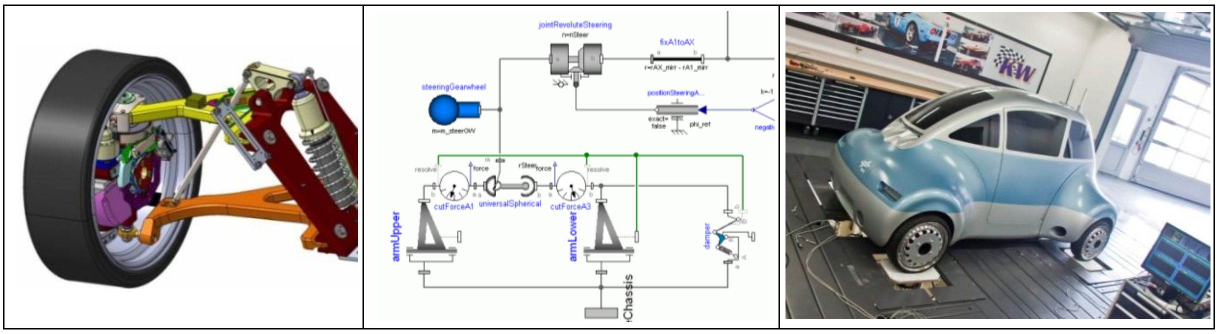

Figure 3: Suspension design in CAD (left), part of the block diagram of the Modelica multi-body suspension model (middle), validation on 7-post shaker test rig (right)

Parameter	Value	Parameter	Value
Natural frequency – sprung mass (front)	1.16 [1/s]	Castor angle (front and rear)	4.0°
Natural frequency – sprung mass (rear)	1.27 [1/s]	Castor trail (front and rear)	25.2 mm
Roll centre height front	72.5 mm	Scrub radius (front and rear)	2.3 mm
Roll centre height rear	81.3 mm	Maximum travel (bump / rebound)	60 / 80 mm

Table 1: Key suspension parameters in the construction position

In order to satisfy these challenging requirements without physical prototypes, the design of the suspension geometry was validated using a multi-body simulation. Detailed models of the suspensions were generated using Modelica, and the static geometric relationships were then evaluated. One example of this usage of the model was for the evaluation of wheel camber variation as the wheels steered through the angle range from 0 to 90°. This is shown in Figure 4-left. The front wheels take on positive camber values of 3.4°, and the rear wheels 11°.

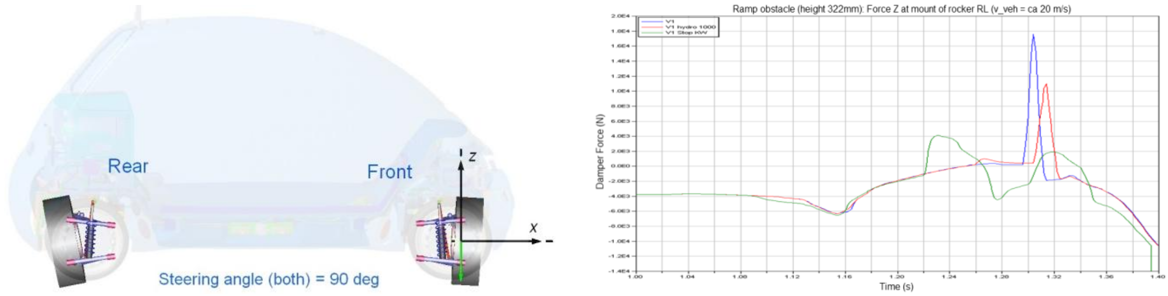

Figure 4: suspension geometry at 90° steering angle (left), damper forces when driving over a bump – red: no rebound stop, blue: with V1 rebound stop, green: with the selected rebound stop (right)

Also important for the design of the mechanical components and mechatronic vehicle dynamic systems are the loads. These are evaluated through dynamic simulations of the complete vehicle model. This task was simplified by using the already available automotive specific features such as driver, road, and tyres in DLR's Modelica libraries. One such application was for the selection of damper rebound stops based on the loads on the rocker as the vehicle (with stops of various properties) drove over a bump, as shown in Figure 4-right.

4. ELECTRICAL ENERGY SYSTEM

The fourth vehicle module is the energy unit. This is a Lithium Ion Battery which has sufficient capacity for a range of 100 km. It is inserted and released from the bottom side (see Figure 3-right) of the vehicle, which corresponds to the concept proposed in [10]. This concept was proposed to allow exchanging the battery instead of charging it at the service station to shorten waiting times, and in the context of the ROMO prototype this allows the possibility of using alternative electrical energy sources in future developments, such as hydrogen fuel cells or the DLR-developed free-piston linear alternator [11].

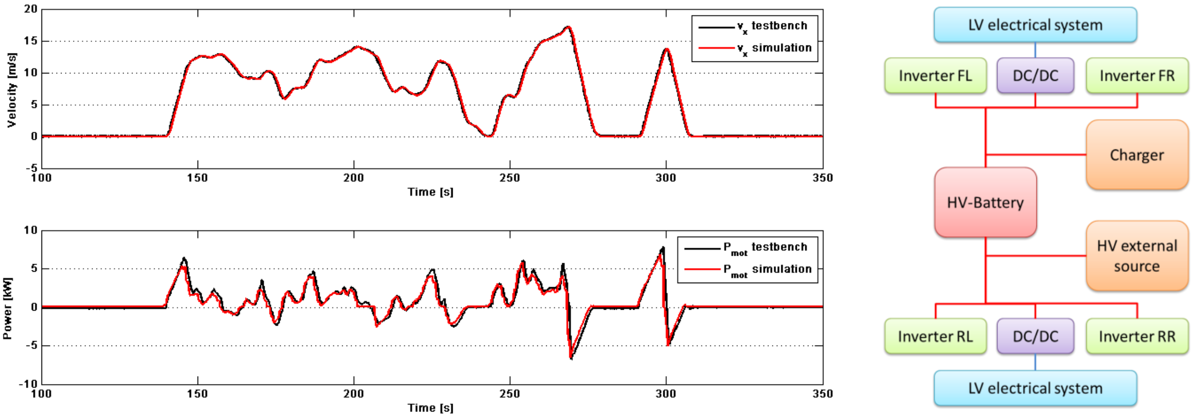

Figure 5: Test bench vs. simulation data of the ROMO negotiating a suburban drive cycle- velocity plot above and power comparison below (left), schematic of the ROMO electrical system (right)

The electrical architecture consists of a high-voltage (HV) battery as the main power source (see Figure 5-right). This is connected directly to the inverters of the four traction motors, and also to two DC/DC converters to supply the low voltage (LV) system. A direct connection with a high voltage DC power supply allows on-board electrical system investigations as well as fast charging of the vehicle. The states of the electrical system are controlled by the BNCU (on-**B**oard **N**etwork **C**ontrol **U**nit), one of the components of the hierarchical controller architecture.

The air-cooled battery unit consists of 90 pouch type cells divided into nine stacks, providing a nominal capacity of 13 kWh at 324V. Simulations show that the ROMO can travel approximately 100 km within the usable SOC range. To ensure operational safety, the HV electrical system is designed in accordance to the ECE R100 regulations for electric and hybrid vehicles. As safety measures for the high-voltage system, an isolation monitor is implemented alongside a HV-interlock signal wire, which ensures that all HV components are connected and secured. Any breach of these security measures leads to a release of the battery main relays.

Development of operating strategies to optimising the energy management requires high-fidelity models of the energy sources and the sinks. In the case of the HV system, these are the Li-Ion battery pack and the in-wheel drive motors respectively. The information from systematic battery cell testing was used to configure and parameterise a real-time capable battery model. With this a model based state observation concept was developed to predict the states within the battery, including state of charge (SOC) and power availability [12].

Recently tests with the ROMO were performed on DLR's chassis dynamometer in Stuttgart. Amongst other tests, drive cycles investigations were performed using an automatic controller on rollers simulating the velocity dependent resistances on the vehicle. The data is then validated with the results from a drive cycle simulation to check the accuracy of the models. In Figure 5 the vehicle followed the so-called “Stuttgart suburban” cycle, a DLR drive cycle based on a speed profile recorded in a real life drive in suburban Stuttgart. The 80% fit of the electric power consumption gives satisfactory results for the first validation of the motor and battery models.

5. FUNCTIONAL ARCHITECTURE

The modular system architecture of the ROMO was developed to take advantage of the design freedom provided by its entirely new development, accounting for the multitude of intelligent mechatronic systems and functionalities. The architecture stems from that of intelligent robots, which involves a hierarchical structure with perception and cognition giving commands to a lower level control (reactive) layer, which then controls intelligent actuators to execute the required actions. An advantage of such a hierarchical layout is the reduced complexity of the intra-system interactions compared to separation by function, while the development of new features is simplified by making use of existing functions. Detailed descriptions of the functions in the ROMO are outside the scope of this paper.

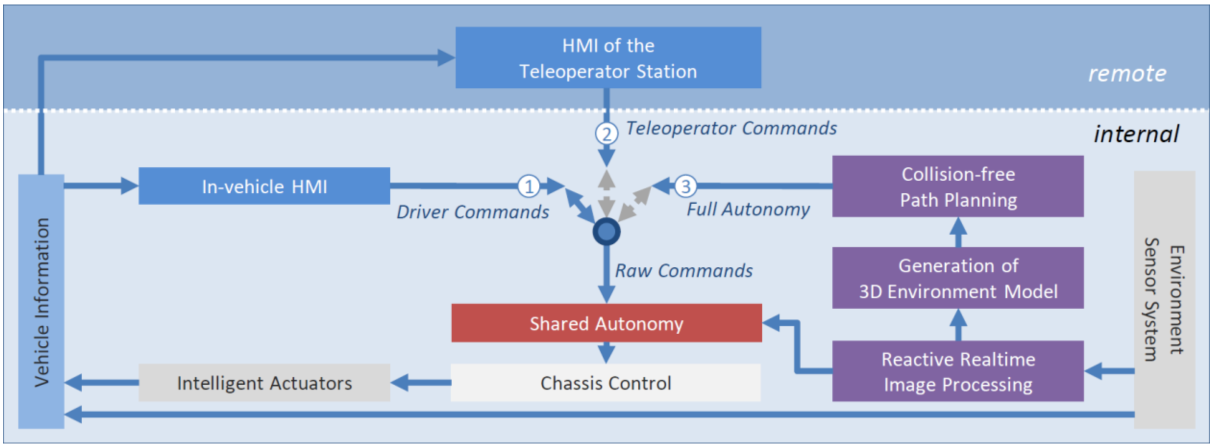

Figure 6: Functional architecture of the ROMO

The flow of commands in the ROMO begins with sensing of the environment and recognition of a motion demand, which can be set by the in-vehicle HMI, by a driver in a teleoperator station, or by a path planner for autonomous driving (see Figure 6). As an essential part of the vehicle concept, machine vision cameras are installed at the front, rear, and top of the ROMO to ensure a 360° view around the vehicle. Cameras are used as the primary kind of perception sensor for their advantages regarding power consumption, depth of information, electromagnetic compatibility, and ease of integration. Different algorithms established in computer vision [13] are adopted to provide the ROMO with all relevant information of its environment. From this a collision-free path for the vehicle is generated. The ROMO employs the concept of shared autonomy, in which the human operator expresses a raw motion demand that is subsequently refined by the subordinate system on its own, using the available information about the environment and the vehicles system states. The human operator is always supervised in this concept. Consequently, the vehicle can refuse to cause an accident. The desired trajectory provided by the Shared Autonomy is then controlled using an advanced global chassis control algorithm based on inverse nonlinear vehicle models [14] combined with online optimisation. A highly accurate estimation of the ROMO's motion is provided by the combination of vision systems and state of the art DGPS-Aided inertial navigation system. This control algorithm generates the demands for the intelligent actuators which interact with the environment. A more in-depth discussion of the vision and autonomy aspects can be found in [15].

6. CONCLUSION AND OUTLOOK

The ROMO project demonstrates opportunities for the future of mobility, showcasing a highly manoeuvrable electric city vehicle with the potential to optimise the use of resources for propulsion and driving dynamics through intelligent sensors and actuators. Technologies are transferred successfully from aerospace applications, such as the Mars rovers, to individual transport solutions on earth. Its development makes use of the latest in model-based design methods, from the models of the Li-Ion battery system to calculating dynamic suspension loads using a multi-body vehicle model in demanding driving manoeuvres. The use of the non-domain-specific modelling tool in Modelica allows reuse of many of these models in different investigations, thereby saving effort. Although the models and investigations in this project are at a proof-of-concept quality that is suitable for prototype development, most of the methods can be applied in multi-disciplinary design of production vehicles.

While much work remains before the commercialisation of the *Wheel Robot* concept is possible, partly due to the need for redundancy in the mechatronic individual wheel steering and brake systems, the resulting spectrum of possibilities in vehicle dynamics and vehicle guidance warrant further investigations.

In the near future the autonomous concepts, teleoperation solutions, energy management and distribution, novel human machine interface concepts based on joystick control [16] and extended safety systems will be implemented and tested. Concurrently, test benches are being developed to validate the *Wheel Robot* concept.

7. ACKNOWLEDGEMENTS

The authors would like to thank Prof. Dr. Martin Otter for his expert advice, Dr. Tilman Buente for his work on the ROMO's vehicle dynamics control, Stefan Hartweg for the flexible bodies simulation, and Dr. Neal Lii for supporting the systems analysis. The authors would also like to thank the BayStMWIVT for their financial support, as well as project partners RoboDrive and RG-Mechatronics for their contribution in the development of the *Wheel Robots*.

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