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Autonomously controlled storage management in vehicle logistics – applications of RFID and mobile computing systems

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Today, planning and control of logistic processes on automobile terminals are generally executed by centralised logistics systems, which cannot cope with high requirements for flexible order processing due to increasing dynamics and complexity. The main business processes on automobile terminals – notification of vehicles by automobile manufacturer, transport to automobile terminal, storage and technical treatment as well as delivery to automobile dealer – are planned and controlled by centralised application software systems. In the context of this article, an innovative approach to autonomous control in automobile logistics is investigated, considering as example the logistic order processing of an idealised automobile terminal of the company E.H. Harms Automobile-Logistics. Within a simulation study, evidence of the existing application potential of autonomous control in the field of vehicle storage management is provided. Thereupon the technical feasibility of an autonomously controlled storage management system is examined. System requirements for technical implementation of an autonomously controlled storage management are deviated. Thereafter, results of an executed case study concerning the implementation and test of an autonomously controlled, radio frequency identification (RFID) based storage management system are presented and the remaining weaknesses of the implemented IT solution are identified. Finally, further research and development activities are introduced in the form of a wearable computing concept using smart clothes.

Keywords: RFID; vehicle logistics; storage management; autonomous control; information and communication technologies

1. Introduction

1.1. Autonomous control in logistics

The idea of autonomous control in logistics is to develop decentralised and heterarchical planning and controlling methods in contrast to existing central and hierarchical aligned planning and controlling approaches (Scholz-Reiter, Windt, & Freitag, 2006). Decision functions are shifted to logistic objects. In the context of autonomous control, logistic objects are defined as material items (e.g. vehicles, storage areas) or immaterial items (e.g. customer orders) of a networked logistic system, which have the ability to interact with other logistic objects of the considered system. Autonomous logistic objects are able to act independently according to their own objectives and navigate through the logistic network themselves (Windt, Böse, & Philipp, 2008).

An essential condition of autonomous control is a high degree of interoperability. Autonomous logistic objects must be able to communicate with other

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objects and exchange data in order to ensure the availability of all relevant data needed for decision-making. Innovative sensor systems as well as other information and communication technologies (ICT) are of particular importance concerning the fulfilment of these fundamental demands of decentralised logistics systems. Technologies such as radio frequency identification (RFID) for identification, global positioning system (GPS) for positioning or universal mobile telecommunications system (UMTS) and wireless local area network (WLAN) for communication tasks enable logistic objects to get information about their system environment and provide the basis for decentralised decision-making in autonomously controlled logistic systems (Böse, Piotrowski, & Windt, 2005). Nevertheless, today the adoption of transponders in the field of automobile logistics is currently confined to a few applications in closed circuits. The main reasons are relatively high costs as well as insufficient standardisation and performance of RFID systems (Böse & Lampe, 2005).

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1.2. *Object of investigation*

E.H. Harms develops and provides complex services for new and used vehicles in the range of transport, handling, technical treatment and storage. The group of companies, consisting of E.H.H. Automobile Transports, E.H.H. Auto-Terminals and E.H.H. Car Shipping, has established a Europe-wide logistics network on the basis of automobile terminals at strategically important traffic junctions. Every vehicle passes a set of process steps in the automobile logistics network: collection of vehicles at automobile manufacturer, multi-modal transport to automobile terminal via road, rail or inland waterway/sea, storage and technical treatment as well as delivery to automobile dealer. This article focuses on the storage management of vehicles of a typical automobile terminal of E.H. Harms Automobile-Logistics.

After delivery, each vehicle is identified by its vehicle identification number (VIN) from the terminal staff using mobile data entry devices (MDE) which can read barcodes placed inside the vehicle behind the windscreen. The VIN allows an assignment of the vehicle to its storage and technical treatment orders stored in the logistic IT system. Based on predefined priorities, the IT system allocates a storage location of a storage area to each vehicle. A handling employee moves the vehicle to the assigned storage location. After removal from stock, the vehicle possibly runs through several technical treatment stations, such as fuel station or car wash. The sequence of the technical treatment stations is specified in the technical treatment order of the vehicle. Upon completion of all technical treatment tasks, the vehicle is brought to the shipment area for transportation to the automobile dealer (Böse, Lampe, & Scholz-Reiter, 2006). Figure 1 illustrates the value chain of vehicle logistics on a typical automobile terminal.

2. Potentials for improvement

Efficient vehicle management in automobile logistics networks requires knowledge about the positions of all vehicles within the system at a given time. Only high

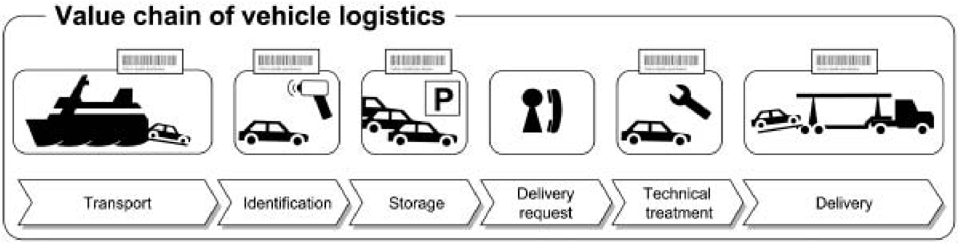


Figure 1. Value chain of vehicle logistics on a typical automobile terminal.

transparency of all vehicle movements in the considered logistics network allows an efficient disposition of available resources on and between the automobile terminals. Thereby, all participants of the automobile supply chain – automobile manufacturer, automobile logistics provider and automobile dealer – have the same demands on storage management: fast and exact vehicle identification, short operation times regarding placing in and removal from stock, high transparency of vehicle locations as well as permanently updated stock levels. According to Gudehus (1999), the storage management tasks of an automobile terminal can be summarised as follows:

- Receiving, storage and control of stock placement and stock removal orders.
- Storage allocation of vehicles based on optimal occupancy strategies.
- Instruction and coordination of storage processes executed by handling staff and shuttle buses based on optimal movement strategies.
- Generation and allocation of transportation orders.

2.1. Organisational potentials

The storage management of vehicles on automobile terminals provides much organisational potential for improvement (Böse et al., 2005; Fischer, 2004). The storage allocation is executed by a centralised planning and control system based on fixed heuristic rules and priorities. This logistic system offers neither a flexible allocation of storage areas and locations considering future process steps (e.g. next technical treatment station after removal from stock) nor an immediate reaction to disturbances (e.g. rush orders, breakdown of technical treatment station) during order processing (Böse et al., 2005). Each vehicle is allocated to a storage location in a storage area on the basis of fixed and predefined priorities. Even though these priorities consider whether there are possible technical treatment orders assigned to the vehicles, there is no differentiation regarding the type of technical treatment and therewith the location of the technical treatment stations which may be a long way away from each other. As a result of the fix prioritisation of the storage areas for vehicles with or without technical treatment orders, a flexible selection of storage areas in consideration of future process steps is not possible. Furthermore, the parking time – meaning the time of a vehicle in a storage area to be parked by a handling employee at a designated storage location – is not taken into account in the scope of the storage allocation process. This is of particular importance due to the fact that the needed parking times of storage areas can differ heavily depending on their stock level. As a result, time saved due to the short distance between current vehicle location and selected storage area is possibly compensated by a long parking time in the storage area.

The insufficient consideration of complexity and dynamics in storage management leads to inefficient planning and control of storage area allocation. The high amount of manual work caused by inadequate use of information technology combined with a huge quantity of planning tasks (e.g. vehicle throughput of 160,000 automobiles in 2004 on the automobile terminal E.H. Harms Auto-Terminal Hamburg) results in time-consuming planning processes with considerable communication and coordination needs. As a consequence of the extensive effort, the quantity of possible planning alternatives is restricted. Furthermore, the selection and evaluation of alternatives is based on the know-how of the dispatcher, which may vary from one employee to another and has therefore an essential effect on the quality of a made decision.

2.2. Technical potentials

The efficiency of planning and control of storage management processing is compromised by incorrect and incomplete data acquisition. The beginning and end of each vehicle movement on automobile terminals is documented via a keyboard or barcode scanner by terminal staff using mobile data entry devices. Although the barcode technology is state of the art, several effects of the weather diminish its functionality. Generally the barcode labels are placed inside the vehicles behind the windscreen. Raindrops, condensate or snow on the windscreen makes scanning barcodes unreliable to impossible. Furthermore, barcodes show a tendency to bleach when exposed to direct sunlight depending on paper quality and printing mode. During long storage periods many barcode labels become unreadable and unusable.

In addition, manual data entry via keyboard in the context of vehicle handling, placing in or removal from stock as well as technical treatment tasks includes the risk of erroneous data and as a result high consequential costs. So the execution of assigned tasks is not confirmed and an outdated process status maintains in the operational IT system. This causes a manual check and possibly a time-consuming search of the related car. All things considered, manual data entry of vehicle movement information via barcode scanner or keyboard is error-prone, time-consuming and concerning its quality dependent on the competence of the responsible employee (Böse & Lampe, 2005). One alternative to counteract the described weaknesses is the adoption of transponders instead of barcode labels, which provides much potential for improvement, in particular:

- *Improvement of data quality:* complete and faultless data entry due to automatic capture of vehicle data stored on the transponder.
- *Process acceleration:* immediate vehicle identification and passage documentation in important terminal areas – delivery area, technical treatment stations, terminal gate as well as storage areas. Prompt notification about vehicles passing the terminal gate allows for direct vehicle disposition. Simultaneous identification of multiple vehicle transponders (e.g. bulk identification of entire truck loads).
- *Reduction of process flows:* decrease of search activities caused by vehicles parked at the wrong storage location.

- *Enhancement of process transparency:* generation of correct vehicle identification, complete documentation of all vehicle movements and an up-to-date vehicle stock.
- *Cost savings:* decrease of costs resulting from faulty data entries. Improvement of process stability, reduction of equipment costs through recycling of transponders.
- *Improvement of working conditions:* simplification of data entry tasks through more comprehensive and improved computer-aided support.
- *Protection and improvement of the market position:* development of competitive advantages due to early adoption of new information and communication technologies in association with innovative logistic planning and control methods.

3. Simulation study

3.1. *Objective target*

To realise the potentials for improvement concerning storage management and the related vehicle movement processes described above, a decentralised decision-making approach for autonomously controlled logistics systems was developed. Due to the fact that the development of this approach is not a crucial point of this article, this point is not detailed in the following (for further information, compare Böse & Windt, 2007). According to the definition of autonomous control, autonomous logistic objects are enabled to process information and render and execute decisions on their own. In consequence, both the vehicles and the storage areas have their own master data and act independently regarding their local objective system (compare Figure 2).

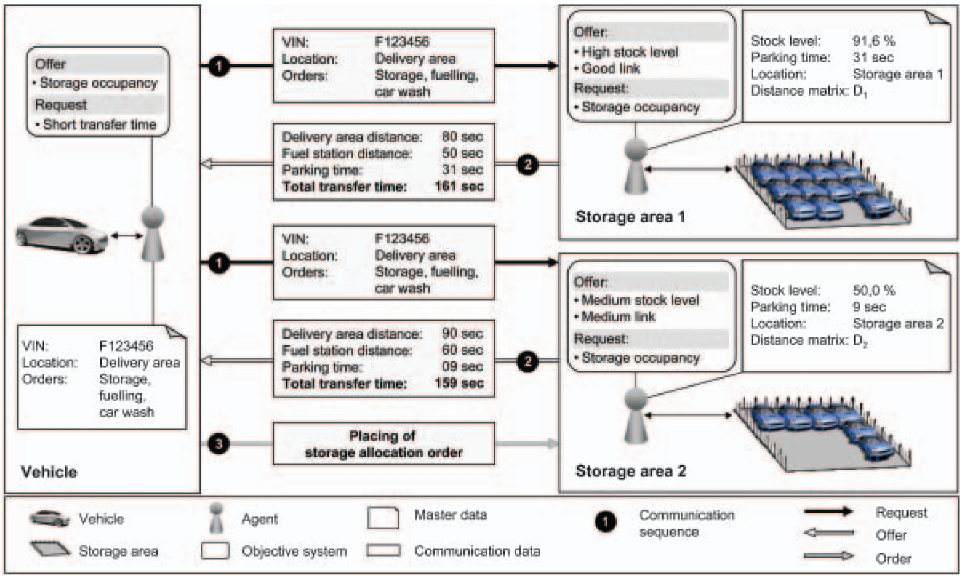


Figure 2. Autonomously controlled decision-making of vehicles and storage areas.

Each vehicle has the objective of short transfer times in the terminal area and provides every single storage area with the occupancy of a storage location. On the other hand, the objective of the storage areas is high storage occupancy. They offer the inquiring vehicle the total transfer time, which consists of the transfer time from the current vehicle location to the storage area, the parking time on the storage area as well as the future transfer time of the vehicle to the first technical treatment station after removal from stock. Depending on the stock level and the position of the storage areas in the automobile terminal, the storage areas can offer a more or less convenient storage time and link to the next technical treatment station. The belonging times described above are added to the total transfer time and transmitted to the inquiring vehicle, which compares the received total transfer times of all storage areas and chooses the best-rated.

3.2. Simulation model

The object of investigation of the simulation study is the transfer times of the vehicles on the automobile terminal. The total transfer time of a vehicle on an automobile terminal TT_{total} consists of the transfer time from the delivery area to the storage location $TT_{storage}$, the transfer time to the technical treatment stations $TT_{technical\ treatment}$ as well as the transfer time from the storage location, respectively the current technical treatment station to the shipment area $TT_{disposition}$ (see Equation (1)).

$$TT_{total} = TT_{storage} + TT_{technical\ treatment} + TT_{disposition} \tag{1}$$

The transfer time from the delivery area to the storage location $TT_{storage}$ is divided into the transfer time from the delivery area to the storage area $TT_{storage\ area}$ and the parking time on the storage area $TT_{storage\ location}$ (see Equation (2)).

$$TT_{storage} = TT_{storage\ area} + TT_{storage\ location} \tag{2}$$

The transfer time to the technical treatment stations $TT_{technical\ treatment}$ is composed of the variable transfer time from the storage area to the first technical treatment station after removal from stock $TT_{technical\ treatment,\ variable}$ and the fixed transfer time between the technical treatment stations $TT_{technical\ treatment,\ fixed}$ (see Equation (3)).

$$TT_{technical\ treatment} = TT_{technical\ treatment,\ variable} + TT_{technical\ treatment, fixed} \tag{3}$$

Finally, the transfer time from the storage location, respectively the current technical treatment station to the shipment area $TT_{disposition}$ consists of the variable transfer time from the storage area to the shipment area $TT_{disposition,\ variable}$ and the fixed transfer time from the last technical treatment station to the shipment area $TT_{disposition,\ fixed}$ (see Equation (4)).

$$TT_{disposition} = TT_{disposition,\ variable} + TT_{disposition, fixed} \tag{4}$$

The transfer times described above show both fixed and variable time slices. For example, the transfer time of a vehicle between technical treatment stations is fixed because of the predetermined handling sequence in technical order processing. For instance, a vehicle is always moved to the car wash after executing technical services or installations in workshops. A variable time slice is the transfer time of a vehicle from the storage area to the shipping area because this time slice depends on the previously made decision regarding the storage area. Recapitulating, only such vehicle movement processes contain opportunities for improvement regarding the total transfer time which have a variable starting or end point. In the considered example, these are the vehicle movement processes from or to the selected storage area in the context of placing in or removal from storage. Each vehicle can determine the best possible storage location and minimise its total transfer time on the automobile terminal area considering the distance between delivery area and storage areas, the stock levels of the storage areas as well as the first destination after removal from storage.

The basis of the simulation study is real vehicle and technical treatment order data of 124,000 vehicles of an E.H. Harms automobile terminal for the time period of one year. In addition to the delivery area, the simulation model includes seven storage areas with an average of 1500 storage locations, nine technical treatment stations with belonging buffers as well as the shipping area. The distances between the technical treatment stations and the several areas of the automobile terminal are represented in a transportation time matrix which contains the transfer times of a vehicle between all considered locations.

Based on the described business processes of the conventionally controlled as well as the autonomously controlled storage allocation, two simulation scenarios are developed as follows.

- *Conventionally controlled Scenario* S_C: the storage allocation is executed centralised on the basis of fixed and predefined rules which contain an order of priority of all storage areas for both vehicles with and without assigned technical treatment orders. Depending on the existence of a technical treatment order, each vehicle is assigned to the consecutively next available storage location on the currently prioritised storage location.
- *Autonomously controlled scenario* S_A: the storage allocation is executed decentralised by the autonomous logistics objects. Each vehicle chooses that storage area which offers the shortest total transfer time. Placing in storage is accomplished chaotically, i.e. the handling employee moves the vehicle to the designated storage area and parks the automobile on the fastest reachable storage location.

Based on these simulation scenarios, two simulation models are developed and investigated by means of the simulation tool eM-Plant. Figure 3 illustrates the implementation of the autonomously controlled simulation model in eM-Plant.

In this simulation model each autonomous logistic object is represented by a virtual agent, for example a vehicle agent. According to multi-agent systems (Ferber, 1999) the vehicle agent has its own master data, which are stored in tables. The objective system and the decision functions for planning and control of the vehicle movement processes on the automobile terminal are described in the form of knowledge-based methods.

3.3. Results

The main results of the simulation runs are illustrated in Figure 4. At first the frequencies of the total transfer times per vehicle TT_{total} of the conventionally

Figure 3. Simulation model of the autonomously controlled scenario.

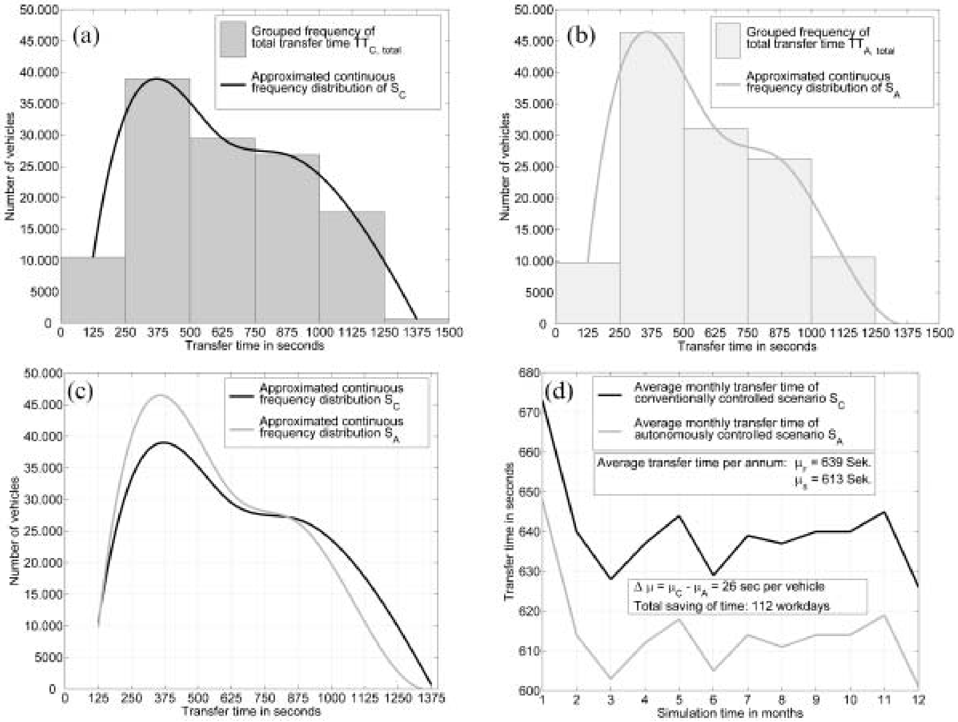


Figure 4. Results of the simulation study.

controlled scenario S_C as well as the autonomously controlled scenario S_A are drawn in respectively one histogram. For the purpose of comparability of these simulation scenarios, a continuous frequency distribution is deviated by approximation (compare Figure 4(a) and (b)).

Merging the two frequencies, a significant upsetting of the curve of the autonomously controlled scenario becomes apparent compared to the conventionally controlled scenario. In the autonomously controlled scenario S_A more vehicles show a lower total transfer time and fewer vehicles a higher total transfer time than in the conventionally controlled scenario S_C (compare Figure 4(c)). Due to the fact that the data pool of both simulation scenarios is identical regarding the number of considered vehicles, the continuous frequency distributions have an intersection. The average monthly transfer time of the conventionally controlled scenario S_C and the autonomously controlled scenario S_A are represented in Figure 4(d). Both scenarios show a similar behaviour of the curve, but the curve of the autonomously controlled scenario is shifted down. As a consequence, S_A has a lower average monthly transfer time than S_C. The distance between the curves varies depending on the stock level of the storage areas. The higher the stock levels of the storage areas the longer the parking times in the case of chaotic stock-keeping and the lower the time saving of the autonomously controlled scenario. The high total transfer times in January result from a large initial stock of the storage areas. The variation of the curve behaviour throughout the year depends on the variable number of moved vehicles and the amount of technical treatment orders. Over the year, the average time saving of the autonomously controlled scenario S_A adds up to 26 seconds per vehicle compared to the conventionally controlled scenario S_C. Over all vehicles, a total time saving of 112 work days arises for the vehicle movement processes on the automobile terminal (Böse & Windt, 2007).

4. Technical implementation

By means of the simulation study described before, the evidence of existing application potentials of autonomous control in the field of vehicle storage management could be provided. As a next step, the technical feasibility of an autonomously controlled storage management of an automobile terminal with today's information and communication technologies is examined. An appropriate technical hard- and software system has to fulfil different system requirements, which are introduced in the following. After that, various alternative solutions of transponder usage on automobile terminals investigated in a previous case study are presented. The best-rated solution is the basis of a developed hard- and software prototype of an autonomously controlled storage management system. The main results of the underlying case study are described at the end of this section.

4.1. System requirements

Based on the storage management processes on automobile terminals described above, several system requirements for the hard- and software system can be deviated. These requirements – containing functional requirements, technical requirements, user requirements as well as safety requirements – have to be fulfilled to support terminal staff in vehicle handling processes and, as a result, to benefit

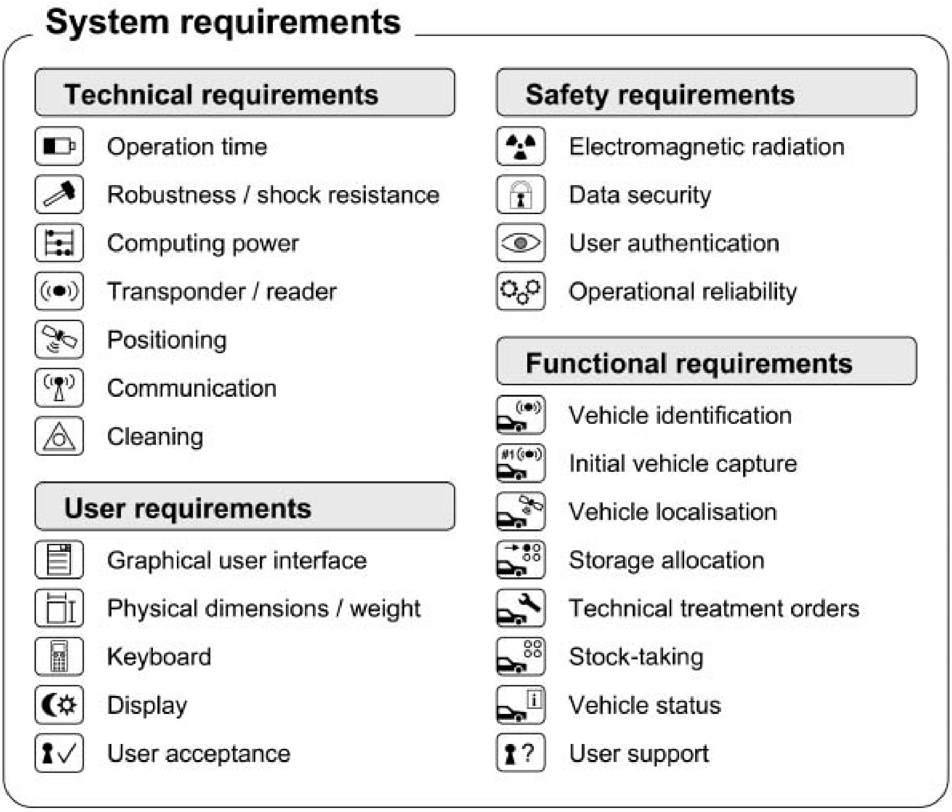


Figure 5. System requirements.

from the introduced potential for improvement. Figure 5 gives an overview of relevant system requirements.

4.1.1. Functional requirements

Based on the concept of an autonomously controlled storage management of vehicles specified before, functional requirements referring to relevant handling processes of vehicles can be derived as follows.

- *Vehicle identification:* unique, reliable and fast identification of vehicles via VIN.
- *Initial vehicle capture:* on delivery, capture of relevant vehicle data (VIN, colour, vehicle type, vehicle damages if required etc.) in the logistic IT system of the automobile terminal.
- *Vehicle localisation:* exact localisation of vehicles on the huge terminal area, real-time vehicle stock of storage areas and allocation of technical treatment stations.
- *Storage allocation:* fast, flexible and optimised storage allocation in the context of stock placement coping with unanticipated disturbances and considering logistic objectives.

- *Management of technical treatment orders:* ascertainment of technical treatment orders (all technical treatment orders, open technical treatment orders, next technical treatment order etc.) and presentation to handling employee.
- *Stock-taking:* fast and user-friendly stock-taking of all vehicles on the automobile terminal.
- *Detection of vehicle status:* simple and fast detection of current vehicle status (waiting for transfer, in process etc.).
- *User support:* support of handling employees in the form of user guidance (e.g. suggestion for next activities) in order processing.

4.1.2. Technical requirements

Compared to the functional requirements, which refer to the functions to be implemented in the application software, these demands relate to technological aspects of technical implementation with main focus on hardware and middleware. Summarised, the main technical requirements are as follows.

- *Operation time:* availability of a power management including standby function to reduce energy demand and consequently extend the operation time of rechargeable batteries (battery capacity of at least 8 hours, which is the shift time of a handling employee).
- *Robustness/shock resistance:* high robustness and shock resistance combined with system reliability of hardware components as a protection against dropping down (up to a height of 1.5 m).
- *Computing power:* providing adequate computing power of the mobile system (central processing unit, main memory) to guarantee short response times of the application software and, as a result, to avoid dead times waiting for completion of data processing.
- *Transponder/reader:* read/write range of mobile transponder reader between 1.5 and 2.5 m, fast reading rate and short response times (< 2 sec.) of transponder reader, setting of reading range via application software or hardware to avoid multiple detection of several vehicle transponders.
- *Positioning:* rapid positioning of the mobile system (< 2 sec.) in the context of stock placement and stock transfer of vehicles.
- *Communication:* providing communication functions for data exchange between mobile data entry device and logistic backend system of the automobile terminal (e.g. based on WLAN, GSM, UMTS), in case of WLAN autonomous selection of the access point with the strongest transmitting power, seamless transition between roaming areas.
- *Cleaning:* easy and damage-free cleaning of applied, mainly outdoor hardware components (mobile data entry devices, reader gates etc.).

4.1.3. Safety requirements

The safety requirements contain several aspects, including health and safety at work, data security as well as system reliability. The safety requirements can be described as follows.

- *Electromagnetic radiation:* compliance with limit values regarding electromagnetic emission (EMA according to DIN 55022, DIN 61000-3-2 and DIN 61000-3-3) as well as electromagnetic interference (EMB according to DIN 55024).

- *Data security:* high data security regarding data exchange between mobile data entry device and logistic backend system (e.g. using encryption standard wireless protected access (WPA)) in case of communication via WLAN), encoding of transponder data to prevent data manipulation or unauthorised readout of data, password protection of the mobile system to secure stored sensitive data (e.g. in the event of stealing or leaving the mobile data entry device inside a delivered car).
- *User authentication:* unique user authentication for quality management purposes (allocation of users to executed activities, increase of data security).
- *Operational reliability:* high operational reliability (e.g. intermediate data storage to guard against power blackout, using emergency power supply).

4.1.4. User requirements

User requirements describe the requirements for the mobile IT system from the user's point of view. These requirements concern particularly the handling of the application software as well as the mobile data entry device.

- *Design of graphical user interface:* easy to use and quickly learnable handling of the application software, comprehensibility and clearness of terminal dialogues, permanent view of common information (e.g. strength of GPS and WLAN signal, status of battery charge, date and time as well as mobile data entry device number), definition of standard font size with respect to a viewing distance of 300 mm.
- *Physical dimensions, weight and handling:* low weight (overall weight including battery < 500 g) and adequate physical dimensions of the mobile system to guarantee its manageability, operating temperature between 10 and 50°C, dust and splash water protection in all weathers, one-hand operation.
- *Keyboard:* use of a lighted keyboard to allow for good readability at night, definition of size and alignment of keyboard with respect to working conditions (usability with gloves etc.), key lock.
- *Display:* image quality, reflection properties and colour scheme (in accordance with ISO 13406-2), good readability of dialogues presented on the display from an angle of view of 20 to 40° (in accordance with ISO 13406-2/7.2) and the keyboard labelling in all weathers (rain, snow, direct sunlight etc.), using an outdoor display, setting of contrast and brightness at the mobile system, backlight.
- *User acceptance:* assistance of terminal staff, low training time and effort, easy-to-use mobile system, no monitoring of employee activities, error-free operation of the mobile system, no limitation of employee competence caused by order processing automation, no impairment of health.

4.2. Investigation of different transponder-based solutions

To counteract the insufficient degree of transparency of vehicle positions in automobile logistics today, first RFID applications in closed circuits can be observed. For example, vehicles stored within some compounds at the automotive manufacturers VW and BMW are fitted with active transponders inside the vehicles to ensure their automatic identification and constant localisation (Buck, 2004). Vehicle positioning is executed by specific vehicles which are permanently moving on the huge automobile terminal area (VW), or by triangulation of the transponder inside the car using a net of antenna-reader combinations (BMW). Possible scenarios of transponder usage on automobile terminals were investigated in the context of a case study (Böse & Lampe, 2005). The main results are described and compared in the following.

4.2.1. *Active locatable transponders*

This solution is characterised by active 2.45 GHz transponders, which are placed in every vehicle on the automobile terminal. The current position of a specific vehicle is defined via triangulation of the transponder attached to it using a net of antenna-reader combinations covering the entire compound. Localisation is executed with an accuracy of 3 m. Gateways of workshops and technical treatment stations have to be equipped with additional devices ensuring that passage and direction of passage can be detected (gate in/gate out). All vehicle positions can be displayed on an electronic terminal plan. The advantage of this solution is the high level of automation regarding vehicle positioning. The main disadvantages are high costs of hardware and infrastructure, i.e. purchase of active transponders and the associated antenna-reader combinations for vehicle localisation.

4.2.2. *Passage control using passive transponders*

To implement this solution, the automobile terminal has to be divided into several storage sectors which can be entered only through gates equipped with antennas and transponder readers. Passing the gate, the vehicle is identified by its passive transponders placed inside the car, e.g. behind the windscreen. The driving direction of the vehicle can be ascertained by arranging two antenna-reader gates in a row. This solution is particularly suitable for gateways of workshops and technical treatment stations. The main advantages are relatively low costs of passive transponders and infrastructure components compared to the first solution. The significant disadvantage is the low accuracy of vehicle positions on the huge storage areas of the automobile terminal and the need to create sectors, which in turn enlarges handling distances.

4.2.3. *Combined solution with transponder localisation*

This solution is based on a combined approach, combining the utilisation of both active and passive transponders. The vehicles are fitted with passive read/write transponders containing the relevant vehicle data. The initial data storage on the transponder can be effected by a mobile data entry device reading an existing barcode and forwarding the information to the transponder. Technical services executed in workshops and other installations are recorded by stationary antenna-readers at entry and exit gates. The handling employees are provided with mobile data entry devices with integrated transponder readers which identify each vehicle by means of the passive tag inside the car and display relevant information (e.g. next destination). In addition, every MDE is equipped with an active transponder that allows determination of the vehicle's storage location. Because every vehicle is moved by a handling employee fitted with an MDE, the storage locations of all vehicles on the automobile terminal are always available through the logistic control system. The advantage of this solution is the relatively low cost of providing each vehicle with a passive transponder. However, infrastructure acquisition costs to enable the vehicle localisation via MDE would be relatively high.

4.2.4. Hybrid solution with GPS localisation

This alternative solution roughly corresponds to the combined solution with transponder localisation. The vehicles are equipped with passive transponders. Operational data can be read from and stored on the tags via MDE. Contrary to the vehicle localisation based on triangulation of active transponders, this solution is based on GPS that allows localisation of the MDE via satellite. Just like the combined solution with transponder localisation, the hybrid solution with GPS localisation is characterised by the low cost of passive transponders. Furthermore, no infrastructure acquisition costs for vehicle localisation through active tags arise. Instead, the MDEs are equipped with a GPS component which allows an exact positioning of the MDE, the handling employee and consequently the vehicle.

A cost–benefit analysis as well as a profitability assessment achieves the following result: considering technical, functional as well as economic aspects, the hybrid solution with GPS localisation is the best solution because of its high practicability combined with its comparatively low costs (for detailed information about the cost–benefit analysis, compare Böse & Lampe, 2005).

Based on the technological equipment of the hybrid solution with GPS localisation, the process chain of vehicle storage allocation can be described as follows: after reading the vehicle and technical treatment order data from the passive transponder placed inside the vehicle, a logistic planning and control software system on the MDE determines the best-rated storage area. After that, the handling employee moves the vehicle to the designated storage area and parks the automobile on the fastest reachable storage location (chaotic stock-keeping). The MDE in place of the vehicle determines its position on the storage area via satellite using the GPS module and communicates the current storage location to the storage area. Because every vehicle is moved by a handling employee fitted with an MDE, the storage locations of all vehicles on the automobile terminal are always available. As a consequence, each storage area has real-time information on its stock level at any time.

4.3. Case study: hybrid solution with GPS localisation

Because of the decentralised data storage and processing, RFID systems provide a good opportunity for implementing autonomous control in vehicle logistics. Therefore, a hard- and software prototype of an autonomously controlled storage management system was developed on the basis of the best-rated hybrid solution. In the context of field tests in April 2006 on the automobile terminal E.H.H. Autotec GmbH & Co. KG in Bremerhaven, the practicability of the hybrid solution with GPS localisation was investigated (see Figure 6). The company T-Systems GEI GmbH was commissioned to procure and develop the hard- and software components. As MDE the skeye.integral from Höft & Wessel was chosen, which is equipped with a UHF reader, an integrated barcode scanner as well as a GPS and

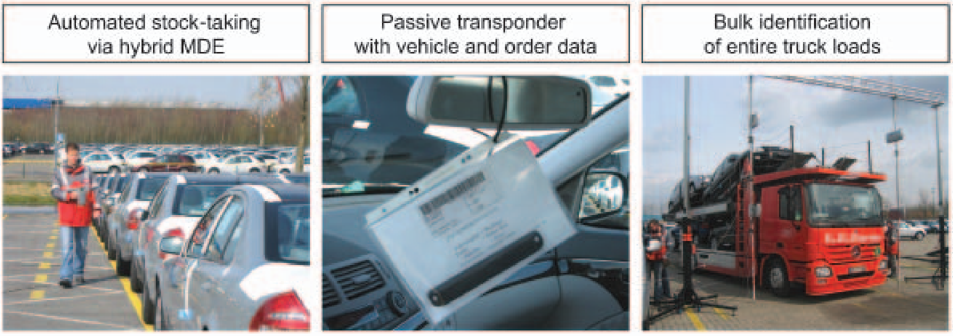


Figure 6. Case study: hybrid solution with GPS localisation.

a WLAN communication module. Furthermore, stationary UHF readers UDL500 from Deister Electronics were installed. The vehicles were fitted with passive Deister ISO 18000-6 B transponders. In this connection, the positioning and alignment of the transponder is of particular importance. Attaching the tag outside the vehicle is only suitable for a limited extent (potential loss of transponder, vehicle damage, difficult attachment and alignment of the transponder). On the other hand, there are several alternatives regarding placing transponders inside vehicles. Case studies have shown that the equipment of vehicles with passive tags in the car boot has little prospect of success due to limited transmitting power of passive tags (Pastillé & Bloch 2006). Therefore, placing the tag behind the windscreen, for instance at the rear-view mirror, is much more promising (Böse, et al. 2006).

4.3.1. Accuracy and operating range of RFID-based hybrid MDE

As described before, efficient storage management of vehicles on automobile terminals depends on absolutely reliable identification. Therefore, the reflection properties of vehicle windscreens were examined in test series with around 100 vehicles of different automobile manufacturers and types. Passive transponders were placed inside the car behind the windscreen at the rear-view mirror. The tag IDs saved onto the transponder were read by a mobile RFID reader. As a result of the test series, 100% of the transponders could be detected at a distance up to 0.5 m passing the vehicles simulating the process of stock-taking. Also, reading and writing of large data volume with around 20 bytes containing vehicle and order data such as VIN or technical treatment orders was possible. In general, the test series showed that the alignment of the transponder to the RFID reader has a significant effect on the operating range. Depending on alignment, it ranges between 1.5 and 3 m. Only some luxury class vehicles are an exception. Transponder data could not be read from or written onto transponders inside the vehicles due to metallisation of the windscreen. Further test series using active transponders from Identec Solutions and the RFID reader TimbaTec Pocket PC from Latschbacher came to the conclusion that these tags placed in luxury class vehicles could be detected due to the higher signal strength of the active RFID system.

4.3.2 Reliability of stationary reader gates

For the purpose of testing the detection reliability of vehicles entering or leaving technical treatment stations, an example gate was equipped with a stationary antenna-reader system which consisted of two UDL500 readers from Deister Electronics. As a result, all vehicles fitted with a passive transponder and passing the gate with an average speed of 7 km/h were identified.

Furthermore, an antenna-reader gate was installed outside the technical treatment station on the terminal area to test the identification of vehicles passing the gate at a greater speed. Around 80 vehicles passed the gate with an average speed of approx. 30 km/h, which corresponds to the maximum speed on automobile terminals. Again, 100% of all vehicles could be detected. Tagged vehicles placed on trucks passing the reader gate with an average speed of 7 km/h could also be identified reliably. Supposed disturbances caused by the superstructure of the trailer did not appear.

4.3.3. Accuracy of GPS localisation

The hybrid solution was characterised by a vehicle localisation using an MDE with integrated GPS module. The verification of the accuracy of GPS localisation reached the expected results. Test series realised on several days with different weather conditions have shown a variance of 5 to 10 m between measured position data and given position data of considered reference points on the automobile terminal. The accuracy of GPS localisation near high-rise storages or technical treatment stations was up to 20 m. Inside these buildings, GPS localisation was not feasible.

4.4. Consistent further development

The case study regarding implementation of the hybrid solution with GPS localisation has shown that essential system requirements for implementation of an autonomously controlled storage management system could be fulfilled. Nevertheless, some requirements remain unfulfilled. Weaknesses are the low operating time and the unhandiness of the MDE resulting from the compact construction and the associated dimensions as well as the weight of the mobile system. Therefore, consistent further development focuses on the development of a second-generation hybrid solution (see Figure 7) using the potential of wearable computing systems (‘smart jacket’).

The idea of the development is the integration of different ICT components for identification, localisation, communication and user interaction tasks in the work clothes of employees. The integration of electronic systems in clothing is an issue that is currently researched by many taskforces (Kirisci & Morales, 2006). A special technological challenge is the high integration level. Many of the previously developed systems are rejected by the users. This is mainly caused by the deficient ergonomics of the developed work clothes as well as manifold doubts about data security or impairment of health (high radiation of electronic components etc.). Systems directly integrated in a jacket will be more accepted by users than other systems which limit the mobility of the users (e.g. belts including relevant system components strapped around the waist) or the visibility (e.g. head-mounted displays). Furthermore, in the context of vehicle logistics, wearable computing systems have to be fixed closely to the body to avoid damage to the vehicles.

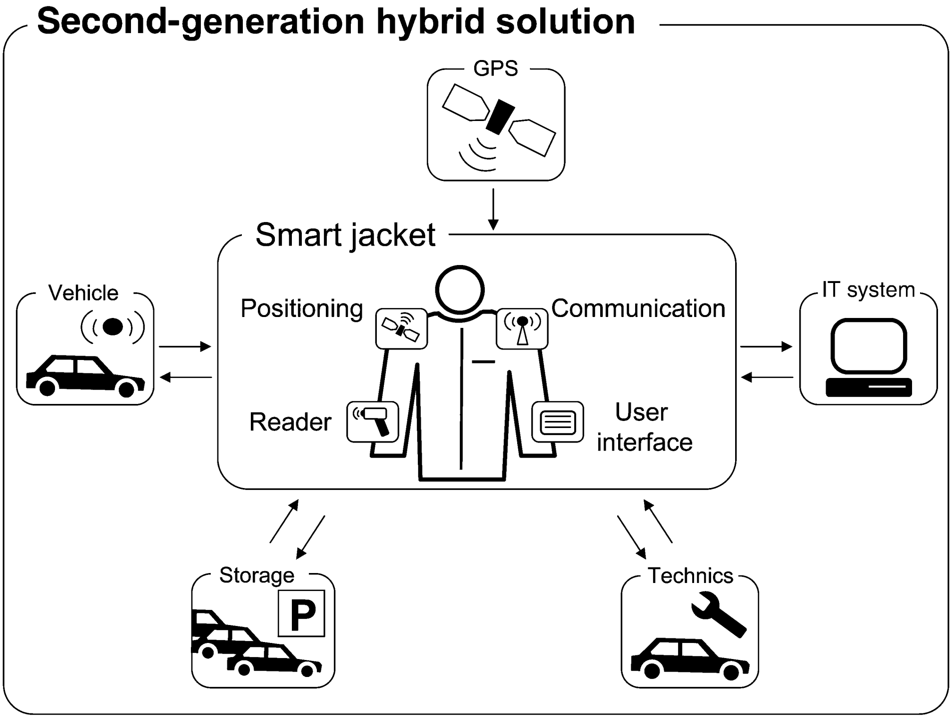
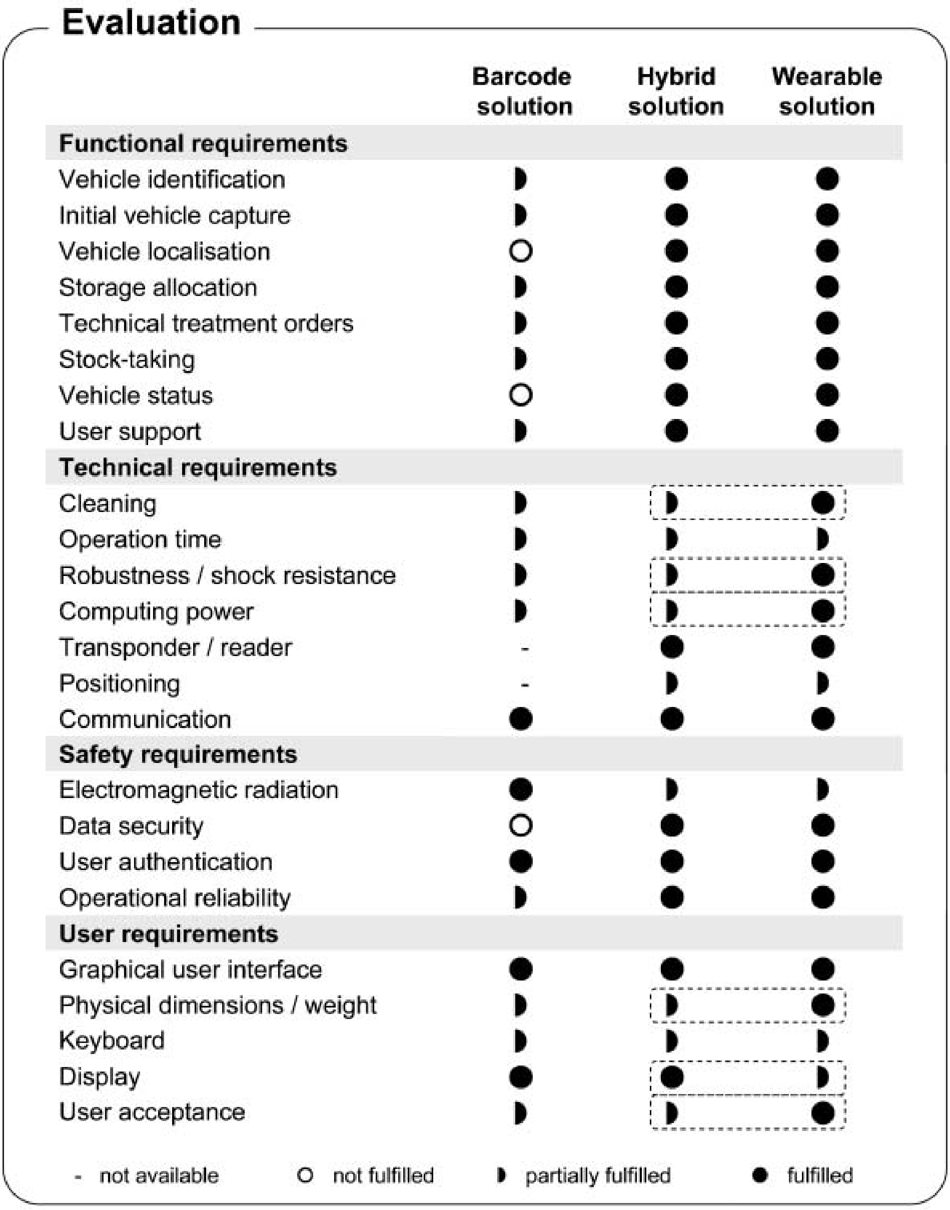


Figure 7. Second-generation hybrid solution – smart jacket.

Figure 8 illustrates the level of fulfilment of the system requirements described above by the barcode solution, the hybrid solution with GPS localisation as well as the second-generation hybrid solution using wearable computing (smart jacket).

The following system requirements are of particular importance to point out both the potential for improvement and weaknesses of the wearable computing solution compared to the barcode and the hybrid solution.

- *Cleaning:* compared to the covers, the keyboards and displays of MDEs are often vulnerable to inappropriate use of detergents. Wearable computing solutions with attached technical components, for example using Velcro fasteners, can be washed without damage to electronic components.
- *Robustness/shock resistance:* the integration of system components in textiles increases shock resistance. The textile layers act as protection against clashes, whereby the endurance of the system can be extended.
- *Computing power:* the distributed design of technical components attached to the smart jacket allows the integration of greater and, as a result, more powerful computing units compared to conventional mobile data entry devices.
- *Physical dimensions, weight and handling:* another advantage of the distributed design of the smart jacket is the weight distribution compared to mobile data entry devices.
- *Display:* the integration of a display in a wearable computing solution is more difficult than in mobile data entry devices. Displays can be installed on the sleeves



Evaluation

	Barcode solution	**Hybrid solution**	**Wearable solution**
Functional requirements			
Vehicle identification	◗	●	●
Initial vehicle capture	◗	●	●
Vehicle localisation	○	●	●
Storage allocation	◗	●	●
Technical treatment orders	◗	●	●
Stock-taking	◗	●	●
Vehicle status	○	●	●
User support	◗	●	●
Technical requirements			
Cleaning	◗	◗	●
Operation time	◗	◗	◗
Robustness / shock resistance	◗	◗	●
Computing power	◗	◗	●
Transponder / reader	-	●	●
Positioning	-	◗	◗
Communication	●	●	●
Safety requirements			
Electromagnetic radiation	●	◗	◗
Data security	○	●	●
User authentication	●	●	●
Operational reliability	◗	●	●
User requirements			
Graphical user interface	●	●	●
Physical dimensions / weight	◗	◗	●
Keyboard	◗	◗	◗
Display	●	●	◗
User acceptance	◗	◗	●

- not available   ○ not fulfilled   ◗ partially fulfilled   ● fulfilled

Figure 8. Evaluation of different technical solutions based on the system requirements' fulfilment.

of a smart jacket. Fixed displays are objectionable due to the required flexibility of the display. Flexible displays also offer a worse representation of dialogues.

- *User acceptance:* systems directly integrated in a jacket will be more accepted by users than other systems which limit the mobility or visibility of the user.

5 Conclusions and outlook

This paper concludes that autonomous control combined with innovative information and communication technologies, especially RFID, is becoming increasingly important to the industry of automobile logistics. Storage management processes on automobile terminals offer a wide range of organisational and technical potentials for improvement. The results of a simulation study considering the storage management of vehicles of a typical automobile terminal of E.H. Harms Automobile-Logistics have shown that establishing autonomous control leads to a higher performance of the system in the form of a better achievement of logistic objectives such as low lead times or high due-date punctuality. As a main result of the various researches into innovative IT-based storage management solutions and the executed case study considering the development of the hybrid solution with GPS localisation, the authors came to the conclusion that the technical implementation of an autonomously controlled storage management system is already possible with today's information and communication technologies. Even though the hybrid solution is the favoured alternative, taking technical, operational and economic aspects into account, some weaknesses of this alternative solution remain due to unfulfilled system requirements. These are, in particular, technical and user requirements. Therefore, further research and development activities focus on the development of a second-generation hybrid solution using the potential of wearable computing systems.

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