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Dependable System Design for Assistance Systems for Electrically Powered Wheelchairs

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Abstract.
In this paper a system design approach is proposed, which is based on a user needs assessment and a flexible and adaptable architecture for dependable system integration. The feasibility of the approach is shown on the example of an assistance system for electrically powered wheelchairs. The system requirements correspond to the cognitive and motor abilities of the wheelchair users. For the wheelchair system built up based on a commercial powered wheelchair several behaviors have been realized such as collision avoidance, local navigation and path planning well known from robotic systems, which are enhanced by human-interfacing components. Furthermore, the system design will be highlighted which is based on robotic systems engineering. Due to the fundamental properties of the system architecture the resulting assistance system is inherently dependable, flexible, and adaptable. Corresponding to the current situation and the users' abilities the system changes the level of assistance during real-time operation. The resulting system behavior is evaluated using system performance and usability tests.

Keywords: dependability, system design, user needs assessment, requirement analysis, use cases, system architecture, evaluation

1   Introduction: Motivation, State of the Art, and Research Question

According to a survey of the University of Berkley, California, published in 2002 the number of computing systems used in everyday life is expected to grow at a percentage rate of 38% per annum. At the same time, the degree of complexity of these computing systems is increasing. Some specialists even warn [1] about this "nightmare of pervasive computing" due to the inability of the system designers to anticipate, design, and maintain such complex systems interacting with each other which can result in catastrophic consequences especially when dealing with safety-critical systems. To enable system designers to develop such complex systems consisting of hard- and software and to consider human factors, an appropriate system design approach is required. This system design approach should, on the one hand, offer methodologies which enable the integrated consideration of these three system components, and, which, on the other hand, supports the dependability of the overall system, thus, decreasing the possibility of a sincere system failure.

A system design approach which meets these requirements is introduced in the following sections theoretically and demonstrated exemplarily on the demonstration platform "assistance system for powered wheelchairs".

2 Dependability-Centered System Design Considering Software, Hardware, and Human Factors

The dependability-centered system design approach advocated here consists of a number of steps, which are thoroughly described in the following.

2.1 User Needs Assessment

A user needs assessment is an evaluative study or an experiment that gives answers about the condition a system is attended to address (cf. [2]). It may also be used in order to compare or prioritize different needs which can be tackled. In order to derive these answers, different methodologies are available (for an overview cf. [3, 4]) ranging from qualitative research designs such as formative scenario analyses or future workshops to quantitative experiments. As thoroughly described in [4] each method provides important insights and has its own advantages and disadvantages, such that only a multi-method approach [5] allows deriving meaningful and valid results. While the quantitative research methods offer a high internal validity, so that a found effect can with great certainty be traced back to the experimental manipulation; they only have a low external validity, which reflects the poor generalizability of the results to other settings, other persons and other timings. This is the case as the experiments take place in a restricted laboratory environment [6]. Vice versa, the qualitative methods allow generalizing the results; however, the results can only to a limited extent be traced back to a manipulation. This is the case as other causes such as sample biases cannot be eliminated [6].

With regard to the wheelchair application the user needs assessment was realized in one study, during which about 15 participants with different types of disabilities executed a gardening task (for a more thorough description, see [7]), and in an experiment, during which about 20 healthy participants drove through a standardized course in a realistic office environment with a given electrically powered wheelchair, however, with different control methods (for a more detailed description, see [8]). In the above introduced classification, the first study reflects a qualitative research method design, as it does not contain any experimental manipulation (all participants executed the same tasks with the same tools). In addition, the participants were asked to fill in unstructured questionnaires. Hence, the study allows generalizing the results. The second data acquisition was an experiment in the classical sense, although the experimental manipulation was a within-subject manipulation and not a between-subject one. The experimental manipulation, we were interested in, is the control mode of the wheelchair. On the one hand the wheelchair could be steered with a standard joystick; on the other hand, the wheelchair was controlled with a two-switch control reflecting a speciality input control device. While a between-subject

experimental variation would have requested us to split our pool of participants and let one group execute the course with the joystick control mode; the second group would have been asked to use the two-switch control mode. Due to the small number of participants, which was available, we asked each participant to drive through the course twice – the first time with the joystick control mode, the second time with the two-switch control mode. While driving we collected data on the collisions which were evoked by the driving behavior of the participants.

The results of the study are two-fold: On the one hand, the questionnaire/qualitative data indicated that especially people with spasticities have troubles operating a standard joystick especially in acute phases. In addition, they have troubles interpreting figural information, e.g., a city map. Furthermore, people suffering especially from incomplete paralysis have deteriorating abilities which requires them to continuously adjust their wheelchair such that they can benefit from it in their everyday life. On the other hand, the quantitative data derived from the study (for a thorough description of the data analyses, see [9]) shows that the variation of the cognitive and fine motor abilities of the participants is quite large and that this variation is to a great degree predictive for behavior differences for wheelchair users.

The experiments' results (cf. [10]) demonstrate that individual differences in the fine motor abilities of the participants were highly indicative about their wheelchair behavior. This refers e.g. to the number of collisions which occurred while driving through the realistic office environment, but also to the velocities driven or to the number of input commands administered to the technical system at hand.

Hence, by applying different research methods for the user needs assessment it enables us (1) to actually trace back the found effects to the individual differences of the users and (2) to generalize this effects to other samples out of the wheelchair population. It is, thus, a thorough basis for deriving the system requirements.

2.2 System Requirements

The goal of this step in the dependability-centered system design approach is to derive a description of the system, which matches as many as possible of the identified user needs. In order to yield these system requirements, the process advocated is based on the ISO Norm 13407 and the socio-cognitive engineering approach. More specifically, a workshop with the design engineers should be conducted, during which the following steps need to be covered:

- specifying a design concept which does meet the needs of the potential users, e.g. by using the design ideas of potential users as an important source of inputs for the design concept
- generating a space of possible system designs, which will make the design concept more concrete by working out different ways of design ideas which will enable to achieve the set design concept
- specifying the functional and non-functional aspects of the system (including the technical specifications) – the functional and non-functional aspects of the system at hand will be worked out for all possible system designs and the one chosen, which, from a technical point of view, yields an optimal solution to the perceived problem situation of the people in need and their task model

- yielding feedback on the functional and non-functional aspects of the envisioned system on the basis of qualitative research methods

In order to derive these system requirements on the example of the assistance system for electrically powered wheelchairs, the results of the user needs assessment were thoroughly presented during a workshop and potential design ideas discussed and reviewed. One potential solution was reflected in a wheelchair which offers high assistive functionality. If, e.g., global navigation and collision avoidance was provided to the wheelchair user, this should have the potential (1) to significantly reduce the possibility of the occurrence of safety-critical situations, as it reduces the impact of the user's input on the wheelchair behavior, and (2) to improve the disadvantages of today's wheelchair control when applying speciality input devices (e.g., reduce the number of input commands, reduce the time required to reach a goal position, optimize the distances to reach an object, etc.). This design idea was then presented to stakeholders. While the actual users liked the idea of a highly autonomous wheelchair, critics came from nurses and physicians, who feared skill degradation. Due to these issues, a nearly autonomous wheelchair as a potential design solution was rejected and another design worked out, which has actually reached positive feedback from all stakeholders and which is described in the following:

Due to the great variability of abilities within and between potential users and their severe impact on the occurrence of safety-critical situations and human performance differences, an assistance system for electrically powered wheelchairs should first of all offer different levels of autonomy, which provide different levels of assistive functionality to the user. Second, these levels of autonomy should automatically be adaptive to the current ability level of its user (cf. [10]). The automatic adaptation is crucial to offer as much support as necessary in this moment, but not as much support as possible. In addition and especially due to the problems related to the interpretation of figural information for some users with specific disabilities, not only the level of autonomy should be adaptive, but also the content representation on the interface. Besides these functional requirements, non-functional requirements with regard to the dependability and the maintainability of the overall human-technology system were set.

2.3 Use Cases

In order to guarantee the common understanding of the envisioned system, use cases need to be worked out in a next step, which describe how a typical user might use the system at hand (cf. [11]).

On the example of the assistance system for electrically powered wheelchairs, the following use case has been worked out:

A wheelchair user with spastics, which are currently on a low level, uses the - in the previous section - described adaptive assistance system. After the first interactions with the system, the assistance system knows about the user's current good ability level and activates the low assistance functionality mode. This low assistance functionality mode uses a collision avoidance behavior on the basis of ultrasonic sensors and prevents the wheelchair from colliding with objects in the

environment. No additional assistive functionality will be given to the user. Due to the ongoing human-system interaction and communication, the technical system is capable of recognizing changes in the current ability level of its user, for example, due to the confrontation with a stressful situation. If this is the case, the system changes its mode and activates an autonomous navigation mode, which does not only prevent the wheelchair from colliding with moving and stable, positive and negative obstacles, but also drives the user autonomously to a – from him/her – desired goal position. In order to enter such a desired goal position, a touchscreen is mounted on the wheelchair, which offers different content representations. While, it could display a floor map of the apartment and request from the user to click on the position, he/she would like to be driven to; it could also in a first step display a list of rooms available in the apartment and if one room has been selected, a list of objects as goal positions could pop up, from which the correct one needs to be chosen by the user. Depending on the automatic assessment of the user's current abilities (cf. [12, 13]), which also underlies the activation of the assistive functionality mode, the system could define the content representation which can without great cognitive effort be interpreted by the user, such that the possibility of a wrong entry is reduced.

Hence, such and more detailed descriptions of how the system will be used from a broad range of users allows the engineers to reduce misunderstandings of the system requirements and offers a deep understanding of the system to be developed, being, thus, an important basis for the following system design step.

2.4 System Design

In order to actually realize the system as envisioned, a system design approach needs to be worked out. In order to support this step, it is recommended to use the component-based design process *KobrA* [14] and to enhance the process with methods for system architecture design [15, 16] and dependability assurance methods. This developed design process provides methods to define functional and non-functional properties, top-down design and bottom-up integration of features as well as methods for testing and assessing the system during run time (online monitoring). Because human-technology-interaction is more and more one of the most critical factors for designing dependable systems with human involvement, a special focus has been placed on specifying the interfaces between humans and technical systems. As statistics (cf. [17, 18]) demonstrate, in 1960 only about 20% of system failures could be attributed to the so-called human factor, this percentage has risen up to 90% in the 1990s.

The component based design method KobrA2.0 has been utilized during the wheelchair development process. The design method is based on orthogonal views of the system and components and on a strict separation of specification and realization. KobraA2.0 promotes stepwise component decomposition at different abstraction levels, components view levels, and components decomposition levels. It includes both "top-down" elements and "bottom-up" approaches, which are suitable for an efficient prototypal system realization. The generic design method is compatible with the developed system architectural concepts as well as with all relevant component

types. The possibility to define a quality level and built-in tests during the design process is an essential part of the seamless design method.

The Recursive Nested Behaviour-based Control (RNBC) Structure [15], possesses properties necessary for building a complex yet dependable system. The fixed structure and the hierarchical nesting of the behavioural levels (the lower, less complex behaviours are embedded within the higher, more sophisticated behaviours) ensure the stability and predictability of the system's behaviour. Due to the fact that interactions only take place between neighbouring levels (recursiveness), the communication effort is moderate and well-defined interfaces ease the implementation of different levels by co-operating work groups. Because of the recursive extensibility, prototypes built bottom-up are operational through-out all development stages.

The development process starts with the identification of the fundamental behaviours, i.e axis-level control, robot-level control, collision avoidance, local navigation, and global navigation. The behaviours are sorted according to the required dynamics starting from the slowest behaviour on the top of the structure.

In the next step, the behaviours will be connected according to the required input and output signals within one level building one unique interface to neighboured levels. The behavioural levels will be connected recursively corresponding to Fig. 1 building the overall system structure of the wheelchair. Additional to the functional interfaces the behavioural levels provide interfaces for system monitoring and reconfiguration.
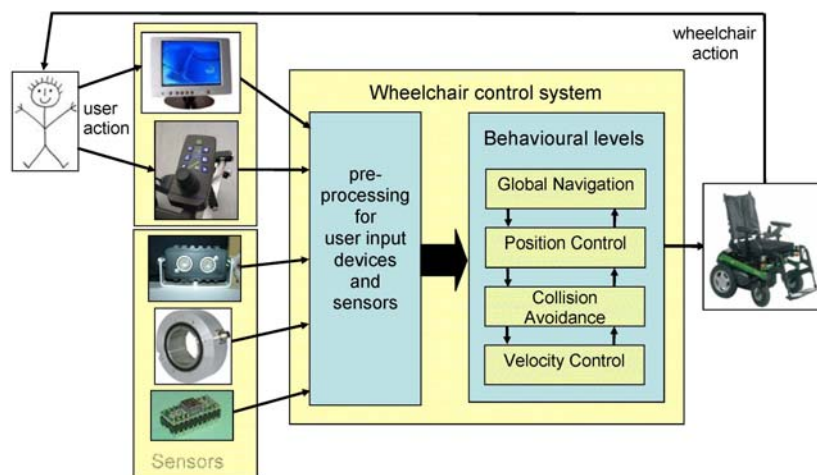
Fig. 1: Control system of the assisted electrically powered wheelchair

This overall system structure, can be utilized further on in the KobrA2.0 component specification process, while the behavioural levels are related to the system decomposition phases (in each phase one new level is tackled) and the behaviours within one level are related to the component decomposition (each behaviour states one basic component, which may be separated into functional components at the bottom of the decomposition process).

2.5 System Implementation

Since the assistance wheelchair is based on a commercial electrically powered wheelchair (OttoBock Healthcare GmbH), the mechanical setup, and some further components and behaviours are predefined, e.g. the axis-level velocity control behaviour. This must be considered in the definition of interfaces, the realization of upper level behaviours and the integration of components.

The overall system structure must also be reflected by the sensor configuration on the corresponding behavioural level. The velocity measurement is enhanced by incremental encoders on the wheel axes and by a gyro measuring the angular rate of the wheelchair orientation. The ultrasonic sensors are arranged around the wheelchair in order to detect a broad class of possible obstacles. However, for geometrical and physical reasons not all kinds of obstacles can be detected by ultrasonic sensors, e.g. holes in the floor or stairs. In order to avoid critical situation during backward driving additional infrared sensors are mounted on the rear side of the wheelchair, which are able to detect descending stairs.

According to the system architecture (Fig. 1) the behavioural levels and the corresponding components can be realized separately, which is described in the following.

Axis-level velocity control

The axis-level velocity control is a pre-fabricated component, which is integrated in a separate control system. It consists of a cascaded control structure for motor current control, velocity estimator and a feedback velocity control for the single driven wheels. In the basic system the input signal originates from the joystick output. The joystick provides the reference velocity vector (magnitude, angular rate), which is transformed into axis-level references using the inverse kinematics of the wheelchair. Depending on the selected mode, the joystick signal is modified by upper level behaviours.

Robot-level velocity control

The robot-level velocity control uses the reference velocity from the upper level and the velocity sensor signals (encoder and gyro) to calculate the velocity error. This error is compensated by a proportional integrating (PI) controller. Since the velocity measurement is error sensitive against bias drift, slippage and mechanical errors both sensor values are fused, in order to combine the advantages of both sensors.

Collision Avoidance / local navigation

A reflexive collision avoidance behaviour is realized based on the artificial potential field method [19]. This method enables a fast reaction on moving obstacles without knowing the exact position of the objects. The original algorithm which determines concentric virtual forces F_i has been enhanced by a momentum vector M_{rot}, which reflects the asymmetry of the wheelchair in relation to the centre of rotation (see Fig. 2.). According to the resulting forces and momentum the velocity reference coming from the upper level is modified and forwarded to the velocity control level in order to ensure a safe navigation.

Local navigation

The local navigation behaviour ensures, that the wheelchair is able to reach way points or goal positions using a fuzzy control structure. The reference positions are provided by the path planning behaviour. Since no global positioning is available for indoor navigation the position control uses the fused sensor signals from the wheel encoders, the odometry and a dead reckoning algorithm in order to calculate the actual position. The actual position may be updated if absoluteposition is provided by an additional sensor.

Global navigation

The global navigation behaviour is based on the A* path planning algorithm, which calculates the shortest way between a staring point and a goal point for a given topological-metric map of the environment.
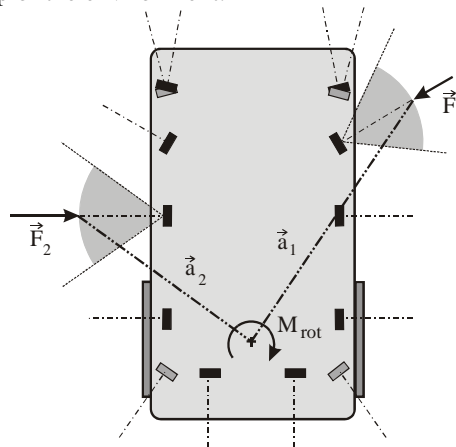
Fig. 2: Ultrasonic sensor configuration (small black and grey boxes), virtual forces and momentum calculated by the collision avoidance algorithm.

User command interface

The user command interface consists of a touchscreen and a conventional wheelchair joystick, which is adapted from the original wheelchair, i.e. the wheelchair driver can use the wheelchair in the non-assisted mode, without any drawbacks. Switching on the assisting system, the user is currently requested to input the mode, in which the wheelchair will operate. In the assisted mode the user is supported by the collision avoidance behaviour and the lower levels. In the full autonomous mode the user selects the goal position from a set of pre-defined goals using the touch panel. In a planned extension the automatic recognition of user capabilities and selection of the suited mode will be implemented into the user command interface.

2.6 System Integration and Test

In order to integrate all behaviours described above in a dependable way, a suitable hardware and software system has been setup. Due to the behavioural levels a separation of functionality and a distribution over many components is possible. For the specific system an industrial control PC running the realtime operating system QNX has been selected. The PC is equipped with interface cards for CAN, Ethernet, WLAN, and I²C communication as well as with arbitrary digital and analog channels. The behaviours are integrated as software components which are executed in form of separated processes within the realtime system (Fig. 3. shows lowest three levels).

The behavioural components communicate with each other using interface threads. This ensures the realtime communication without data blocking or collision. The sensor hardware is connected over special drivers. While the behaviours are encapsulated the interfaces are freely accessible form outside. This can be used for a local online-monitoring and reconfiguration process, which is implemented in the next higher behaviour level. The advantages arising from the separation of behaviours has also been used during the functional test of software components.
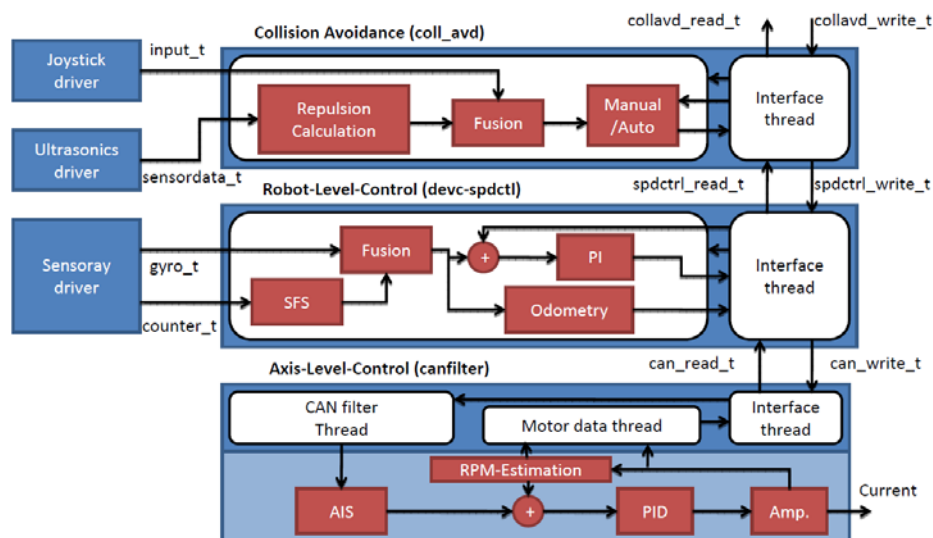
Fig. 3: Software implementation of the wheelchair assistance system.

Thus, the implementation maintains all aspects of the generic system architecture:
- the implementation is flexible due to the free choice of methods and components for the implementation of single behaviours
- the structure is extensible enabling the adding or removal of behaviours
- the signals from and to the layers can be observed locally in order to reduce the development effort due to sparse modelling and communication effort in the running system
- the behavioural levels can be developed and tested separately, ensuring high maintainability

- the user interface is distributed (touch panel for higher levels, joystick on the velocity level) ensuring the input of appropriate signals on the corresponding behavioural level

2.7 System Evaluation

In a last step, the resulting system needs to be evaluated. More specifically, it is to be tested whether the needs, which the system should at least partially reduce, has been met with the system at hand. A systematic approach for an evaluation is provided e.g. by [2] and uses a variety of research methodologies (cf. [6]). In parallel to the procedure described for the user needs assessment is it desirable to combine different methods to yield a greater validity of the results.

With regard to a quantitative evaluation, an experimental set-up can be taken, during which the participants are grouped on the basis of random numbers to avoid systematic selection effects. While a control group executes standardized tasks with a standard wheelchair, an experimental group should perform the same tasks with the new assistance system for powered wheelchair control. During this experiment, a set of variables of interest should be measured, which reflect appropriate operationalizations of the needs.

With regard to a qualitative evaluation, the user's opinions on the new system in comparison to the standard off-the-shelf system can be assessed for example with appropriate available questionnaires or with especially for these purposes constructed questionnaires (cf. [4]).

Due to the great sample size, which is required to yield a high power of the results for these types of evaluations (cf. [20]), we did not use such a between-subject manipulation but a within-subject evaluation. This means, each participant was tested twice – once with the standard system and once with the new assistance system for powered wheelchair control. Such an evaluation procedure has the advantage that the variance, which can be contributed to the subject itself, can be controlled by applying a repeated measurement statistical analysis (cf. [21]).

Such a procedure has been conducted with regard to the wheelchair application and more specifically for evaluating the autonomous navigation behavior. For this purpose, about 20 participants drove through a standardized course twice, once with a two-switch control, once with an autonomous navigation behavior activated. While measuring quantifiable data such as the distances driven and the times required reaching a specific position, a usability questionnaire has been applied in addition in order to gather data on how the participants liked an autonomously driving assistance system. Especially the data on the usability questionnaire demonstrate the superiority of the autonomous navigation mode: nearly in all aspects (i.e. in easiness to learn, intuitiveness, safety, and comfort) the autonomous navigation mode outperformed the manual driving mode.

While this reflects an evaluation of one part of the system, i.e., the autonomous navigation mode, a study evaluating the overall system, which adapts its functionality to the user's abilities, will be conducted in the near future. Such an evaluation will then also give important feedback on this dependability-centered system design approach.

3 Conclusion

This paper aimed at introducing a design approach for dependable complex computing systems considering hardware, software, and human factors. For this purpose, research design methods from the psychological field of formative and summative evaluation (required for the user needs assessment and the final evaluations) has been combined with software tools (e.g., development of use cases, modeling of software components) and implemented in a traditional system design approach covering the development of a system architecture, implementation, integration, and test. On this basis a set of design steps have been introduced which start with a user needs assessment, during which qualitative and quantitative methods are applied in order to identify a need, which the future system should reduce and a system requirement analysis, which defines the functional and non-functional properties of the computing system. On that basis, use cases were developed, which reflect the prototypical usage of the system at hand and which aim at clarifying the chosen design solution. With such a clear vision in mind, a system architecture and control structure can be developed, which is the starting point for the system development. After having implemented and integrated the system, a thorough test phase will ensure that the system meets its specifications. If this phase can be completed successfully, the proposed system development process finishes with a summative evaluation analyzing whether the system is actually capable of reducing the - in the user needs assessment - identified needs. In order to clarify these different steps, an example of an assistance system for electrically powered wheelchairs has been chosen and the results of each of these steps has been summarized in this paper – demonstrating the potentials the proposed dependability-centered system design approach has especially on reducing the possibility of a failure of the human-automation system.

Future work will aim at completing the implementation of the overall system and at evaluating its final version as described in Section 2.7. During this final evaluation a special emphasis will be put on deriving benchmarks, which will enable a fair comparison with other system design approaches especially with regard to dependability. For this purpose, the number of accidents which occurred when using the system in the long run could be compared with the number of accidents when using a system which development was based on another design approach. Other factors which are also indicators about the success of the dependability-centered system design approach can be considered as well. Hence, the evaluation will not only enable judging on the resulting wheelchair system, but also at rating the proposed system design approach and at demonstrating the potential benefits of a design approach considering all aspects of a complex human-technology system consisting of not only hardware, software or human factors, but the interaction of these system components.

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