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MULTIDISCIPLINARY DEVELOPMENT OF NEW DOOR AND SEAT CONCEPTS AS PART OF AN ERGONOMIC INGRESS/EGRESS SUPPORT SYSTEM

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ABSTRACT - Today mechatronic systems are essential for automotive technology. Since their use satisfies the customer's wish for comfort and safety there is great potential for new developments. Therefore five institutes of the Technische Universität München in collaboration with the BMW Group work on a multidisciplinary project which is part of the joint CAR@TUM cooperation.

Based on the example of a support system that reduces the discomfort, which occurs during ingress/egress, the scope of the project is the improvement of mechatronic systems and the development processes deployed.

As constraints and input for the technical realisation in the different fields of development (kinematics, sensorics, and virtual prototyping), ergonomic investigations are conducted. For the generation of the needed ergonomic information a method to measure arising discomfort is built up. By use of this information and in reference to the scenario of narrow parking situations, door kinematics allowing situation-dependent opening paths are developed.

By combining mechanics, a control unit and ambiance information generated by sensors, possible collisions with collateral obstacles can be avoided. The door can be opened situation-dependently to provide optimal room for ingress/egress. Sensors are additionally used to detect an approaching car driver as a basis to personalised preadjustments of the vehicle door path or the seat. The door mechanisms proposed and their actuation are evaluated via user studies by, amongst other things, use of a force-feedback controlled virtual reality system.

Based on the experiences with the development of the presented system a generic process and associated methods/tools to support the multidisciplinary development of mechatronic products are designed.

TECHNICAL PAPER - In today's automobiles mechatronic systems have gained continuously in importance. Integrated as numerous components and connected to in-car networks they are employed to improve comfort and safety for the drivers. Examples comprise automatic gearboxes, automatic climate controls, airbag modules, or vehicle dynamics controls. In terms of electronic engine management with exhaust aftertreatment they also increase car efficiency and reduce emission. Mechatronic systems nowadays are also essential to meet the global homologation requirements and environmental laws. Additionally they give the possibility to meet the customers' wishes.

Despite the advantages achieved, there is still potential for further improvements. In this paper first results of a multidisciplinary mechatronics development project, which is part of the cooperation CAR@TUM between five institutes of the Technische Universität München and the BMW Group, are introduced. Based on the example of an ergonomic ingress/egress support system the overriding scope of the project is to improve mechatronic systems in general as well as the systems' development processes.

The problem dealt with is the everyday situation of ingress and egress in narrow parking spaces which lead to uncomfortable situations for the driver. Particularly long car doors, usually used in two door cars, often cannot be opened wide enough to offer a comfortable and quick ingress/egress. Due to weak door breaks or inappropriate locking positions the driver sometimes even has to steady the door during his movement.

With help of the potential of mechatronics an innovative door system with ingress/egress support is developed. Therefor developer groups of the different disciplines involved have to be merged into a collective development process (Figure 1). Ergonomics provides boundary conditions to ensure usability and avoid discomfort. Considering these constraints kinematics have to be developed that fulfil all necessary functions. By means of sensor data the door movement most appropriate for the actual situation can be chosen and the motion can be controlled by an integrated control system. With a virtual prototyping rig the different concepts of the support system can be simulated and further input for ergonomics and kinematics can be produced.

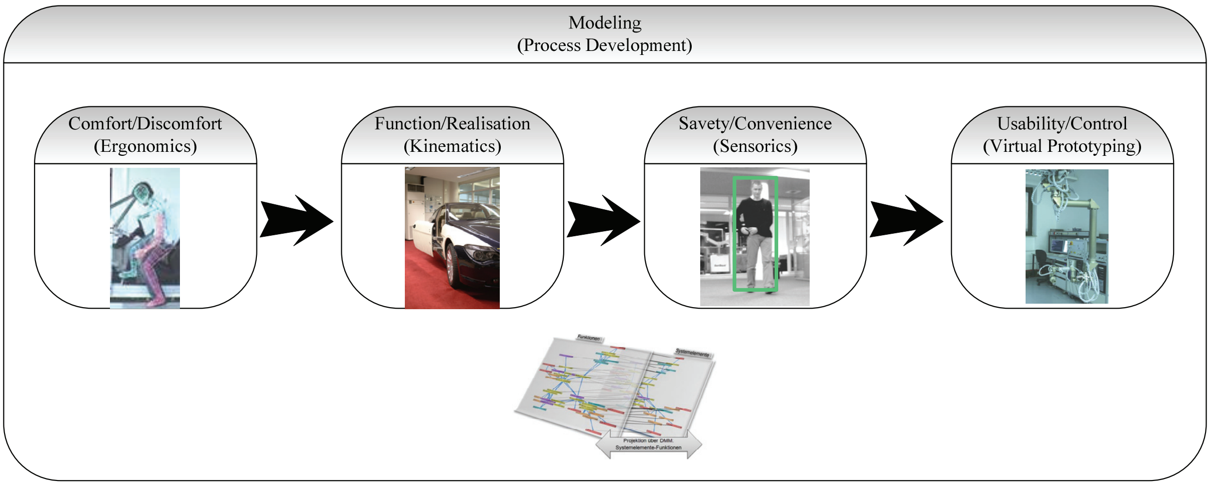

Figure 1: Different disciplines involved in the multidisciplinary door development process: Ergonomics, kinematics, sensorics, virtual prototyping and process development.

STATE OF THE ART, RESULTING TASK AND APPROACH

Historically founded there exist discipline-specific development procedures that have to be improved in detail and integrated in order to allow for the successful multidisciplinary development of an innovative door system.

For example in the field of ergonomics several approaches but no common procedures are known to face the ergonomic challenges. The comfort/discomfort in different ingress/egress situations can be determined by means of multiple simulations or the car interior can be designed using general package data deduced from digital human models like RAMSIS [1]. The appropriate position of driving controls such as the steering wheel, the pedals or the whole seat unit can be ascertained in a 3D CAD environment. The simulations can provide comfort information, but basically include static seating postures.

For the evaluation of car doors these simulation tools can be used for reachability design. To get general information about forces and directions, the handbook of ergonomics [2] can be consulted. In order to improve the design of the car body the influence of the vehicle geometries, e.g. door sill height or A-pillar angle [3], need to be analysed. This arouses the necessity of a new simulation tool that accounts for the discomfort arising as well in certain static postures as during the whole dynamic movement.

Beside the sliding and the – quite rare – wing doors the door concept currently used the most is the rotating door. All these door kinematics have in common that they only employ one degree of freedom (DOF) and hence can conduct only one predetermined door movement. They cannot react to different ambient situations.

In the considered situations with narrow parking spaces rotating doors do not allow an easy ingress into the car. Moreover common sliding door concepts do not fit to sportive passenger cars from the design point of view. In select models alternate door concepts, which again employ only one DOF (e.g. four-bar mechanisms), have been used. To allow a situation dependent and ergonomic ingress/egress, door kinematics, which deploy more than one opening movement, have to be developed [4].

For kinematics development in general various software based tools are available. These mainly provide standard computer input/output interfaces for user interaction throughout the different development steps. For example the specification of the desired paths for the moved part (in this case the vehicle door) can be conducted by the definition of different positions and corresponding orientations (text or point and click based). Alternatively mathematical expressions can be used.

After a synthesis process the results are mostly visualised in sketches or graphs. To learn more about the mechanisms' properties the model first has to be transferred into a CAD-environment and therewith a prototype can be constructed. To allow more intuitive and directed handling of kinematic tasks new design processes have to be implemented like the one presented in [5,6]. The processes have to comprehend all development steps from an intuitive input of the intended (door-) movement, followed by the kinematics synthesis process to a suitable output method for the gained mechanisms.

To get a better idea of the developed kinematics, hardware prototypes have to be available in early stages of development. To realise this in a short period of time rapid prototyping processes can be used to fabricate kinematic elements [7].

Supplement to the prototypes made by rapid prototyping processes virtual prototyping can substitute the construction of physical 1:1 mock-ups, which is often expensive and prone to errors, especially when complex systems are modelled. With virtual prototypes the functionalities and properties of mechatronic systems can be validated [8]. Haptic feedback can be utilized to enable the product designer to explore the kinematic and the dynamic properties of the system. This way, the effects of changing system parameters can be seen instantaneously, and comparative and repeatable user tests can be performed.

Possibly due to the lack of appropriate hardware, little research has been carried out in the field of haptic rendering of large, actuated mechanisms. By means of a high-fidelity haptic device [9], combined with an enhanced admittance control scheme, the authors are able to simulate not only the properties of mechanics, but also the controller and actuation of a novel car door [10, 11]. The combination of both prototyping methods described allows an accurate validation of the proposed door design.

To meet the concerns of the control's safety aspects (collision detection) and the realization of comfort functions (personalised pre-adjustment) sensor information is inevitable. Gathering ambience information is a prerequisite for a safe opening of the door. Yet sensors, such as lidar or ultrasonic sensors described in [13], allow simple distance measurement and fast data acquisition to detect the ambience around the car. However, the detection area of these sensors is small and a set of sensors would be necessary to detect the entire workspace of an opening door. To overcome these limitations sensors with large fields of view have to be integrated into the car door, monitoring the workspace.

For preadjustment of an ergonomic seat position reducing the discomfort during ingress, anthropometric and other data of the car driver is often stored in a personal key [12]. Malfunctions can emerge from mixing up the personalized keys of different persons. They can be avoided by verifying or readapting the stored data. For the determination of the data during the detection of an approaching car driver, the same sensors as for the collision detection can be used.

In the development of the described ingress/egress support system, the integration of the various disciplines causes high product complexity which directly affects the complexity of the linked development processes. State-of-the-art process modeling of multi-disciplinary development processes [14] does not sufficiently enhance the multi-disciplinary system understanding and generates too little awareness of discipline-integrating milestones.

This is due to a distinct decoupling of the representations of the development and production processes on the one hand and the actual system on the other hand. Typical ways of engineering thinking, e.g. function driven vs. component driven understanding of mechatronic systems, further complicate this issue. To resolve these shortcomings the design of a generic development process and supporting methods/tools is part of the presented project. Resulting methods have to improve interdisciplinary system understanding and allow an effective and on schedule integration of the involved disciplines' deliverables. To interlink the discipline-specific development processes more effectively, approaches for the function driven process design and modelling have to be developed. Therefore new product models and process charts have to be developed, that are easy to understand – even across disciplines.

MATERIALS AND METHODS, EXPERIMENTS

For setting the basis of the door development the influences of the car's geometry on the ingress/egress are determined. In a study tests are conducted to specify the influence of restricting geometries (e.g. door sill) to the ease of ingress/egress. 12 subjects (six male/six female) are questioned to their general and local discomfort in exposed body parts with a cp50 scale, while entering and exiting a mock-up with varied restrictions.

The ideal ratio of seat height to street and seat height to car floor, followed by variation of the door sill and roof heights, were tested. Additionally different angles of the upper A-pillar, the lateral roof displacement, and combinations of several geometries were checked. The geometric composition that shows the lowest discomfort can be considered as ideal for the ingress/egress comfort. Additionally a model for both, static postures and dynamic movements, is built up.

To obtain objective data for this purpose, the ingress/egress movements are filmed from two perspectives. Herewith postures can be detected and a posture adjustment can be conducted (Figure 2). The postures are exported to a multi-body simulation tool (MBS) to calculate the arousing momentums in the body joints. The questioned discomfort values determined in previous tests can be compared with the calculated ones in terms of joint angles and stresses. First analysis of the results of an arm/shoulder movement showed high correlations.

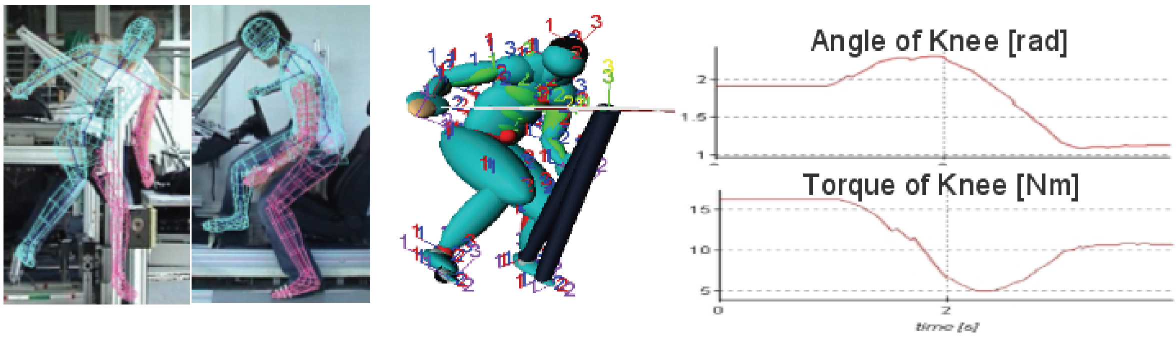

Figure 2: Adjusted posture with PCMAN during ingress from side and front (left); Simulation with a MBS tool (middle); Calculation of posture with MBS-Tool; Example: Maximum torque in the knee (right).

Taking into account the results of the ergonomic experiments, two door concepts – out of different systematically generated designs – were chosen to be prototypically realised. In the first concept an additional link, which connects the door and the car body by means of a second pair of hinges, is inserted into a common rotating door. Hereby a front and side displacement of the rotation axis of the door is realised. To ensure usability, the system's DOF has to be reduced either by means of actuators or by preselectable kinematic structures. By the integration of two actuators (one for each pair of hinges) or one actuator and one rotary encoder the door can be opened in a situation-dependent way [4].

As second concept an innovative sliding door was realised. Especially in narrow parking spaces the door can be opened towards the front or the rear of the car and so release an extensive ingress area. In the realised prototype the door pivots to the side during the opening process and hereupon slides to the front of the car. In order to improve the usability of the door it can be actuated as well. Interlocks have to be included to prevent the door from an incorrect movement. To evaluate the improvements achieved by the new door concepts, prototypes were built up. Therewith the magnification of the ingress/egress room as well as the possibility to avoid barriers could be shown qualitatively.

To realise a directed search for door mechanisms, a prototype of an integrated kinematics development process has been implemented (Figure 3). For an intuitive input of the desired door movement a force feedback controlled industrial robot, which carries a door model, is used. Trajectories of the moved door were recorded [5]. This path information, transferred to a PC, was used for the kinematics synthesis implemented as a parameter variation process.

Different attributes of the mechanism like guide lengths, positions, the available space etc. are varied. The mechanism, that fits best, can now be chosen by the determination of mechanic and ergonomic quality levels (transmission angles, discomfort values etc.).

The first mechanisms (four bar linkages) were synthesised. The actual movement of the door that employs the mechanism obtained by the synthesis process can be simulated by means of the robot. Additionally prototypes were built in a 3D-printing process. The concept's properties and its potential for the improvement of the ingress/egress can be evaluated. Due to low costs and short fabrication duration the process described can be repeated iteratively in short cycles to gradually improve the quality of the found solution. When the solution meets the predefined requirements the concept can be prototypically integrated into a full scale model (e.g. the real car).

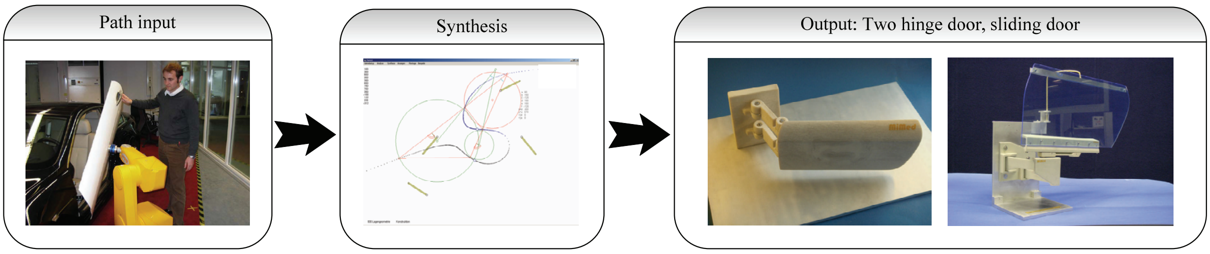

Figure 3: Kinematics development process: path generation, kinematics synthesis, output of prototypes: two hinge door, sliding door.

Before the build up of the full scale model the proposed kinematics are validated by a high-fidelity haptic and visual simulation on a virtual prototyping experimental rig [10], which can be seen in Figure 4. The door is modelled as admittance, i.e. the virtual motion of the door is calculated based on the measurements of the forces and torques applied by the user. Additionally, simulated forces and torques, representing the control action of the car door, can be integrated [10].

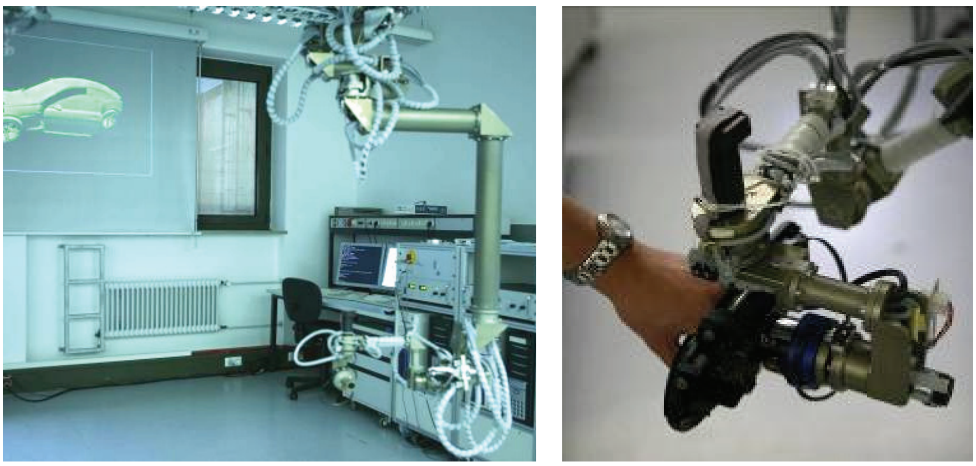

Figure 4: VR simulation of a door concept using the ViSHaRD10 (left) with a dedicated end-effector (right).

The motion of the door is then fed to the position control loop of the haptic device ViSHaRD10 [9], which displays it to the user. Deviations between the desired (= simulated) and the real motion of the end-effector representing the car door are counteracted by an independent joint control scheme. Because of the extraordinary properties of the ViSHaRD10, this allows for a high-fidelity display of the car door kinematics and dynamics. To increase the degree of immersence, a realistic outer door handle is utilized as end-effector of ViSHaRD10.

For the intended situation-dependent motion of the door kinematics ambience information is needed to ensure safety issues. Two vision sensors with a large field of view, integrated in the car door, monitor the entire workspace. The used cameras have a resolution of 752 x 480 pixels with an aperture angle ranging to 130 degrees. Assuming that the obstacles are out of the blind area of the camera at a minimum distance of 50 cm from the car, their distances from the door can be extracted using stereo vision (Figure 5, right).

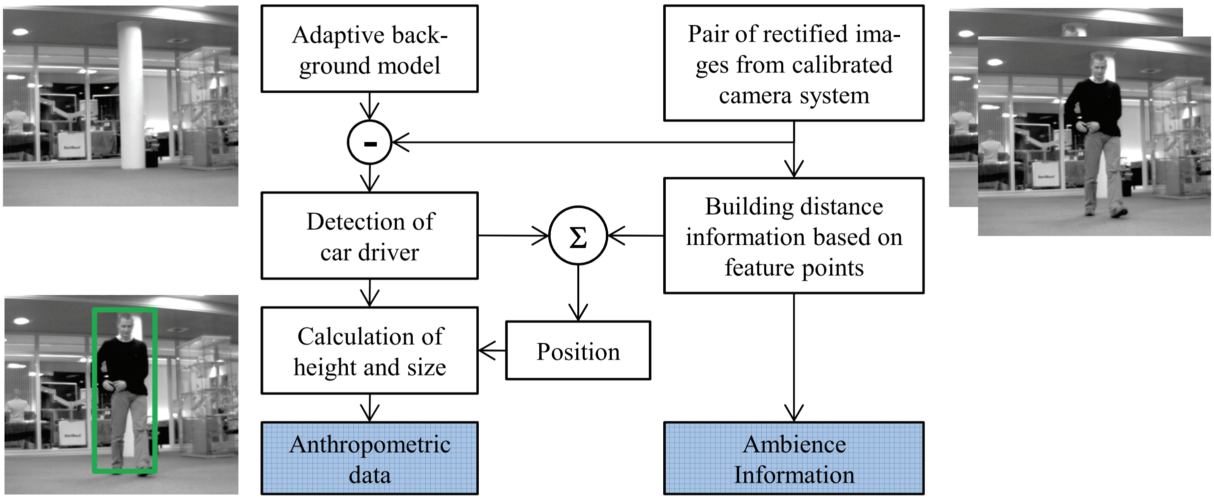

Figure 5: Generation of ambience information with pairs of rectified images from a calibrated camera system using a feature points extractor for distance determination. (right); Calculated anthropometric data of the car driver using an adaptive background model and the distance of the driver to the car (left).

Two images of the workspace are taken by the vision sensors. These are rectified as well via the calibrated distance as the positions of the cameras and the distorted model of the sensors, given by their intrinsic calibration. Distinctive features of the image given by one camera, such as corners or edges, are extracted using the pyramidal Lucas-Kanade feature tracker [15]. The extracted feature points are recovered on a corresponding second image. The pixel coordinates of successfully extracted feature points are stored and their disparity is determined. If a sufficient number of feature points in the region of interest is not available due to a lack of features, the stereo algorithms developed by Abhijit Ogale [16] can be used to provide the disparity map of the workspace. Based hereon a 3D model of the workspace for ambience information is generated.

This model can in turn be utilized by the controller of the car door, e.g. to prevent collisions. By well defined benchmark scenarios, the safety of the operation of the door can be validated through experiments with the proposed VR test bed [11].

The camera system, used for the generation of ambiance information, can additionally realise people detection and anthropometric data generation to support convenience issues. The sensors detect an approaching car driver using an adaptive background model. The model is updated periodically with the actual ambience information and the position of the door with compensation of its ego motion. The car driver can now be detected with a simple difference algorithm: Every new frame of the camera system is compared with the background model. Differences are detected, the approaching driver is extracted, and he is distinguishable from other objects like cars or bicycles. By means of the ambience and distance information, the actual situation and the position of the driver is determined. The anthropometric data for a better ingress can be calculated (Figure 5, left).

The handling of the introduced multikinematic doors cannot be compared to that of common door concepts. Thus, tests are conducted to avoid the possibility of operating errors and assure the ease of handling. Using the RAMSIS software operating reachabilities can be tested and the influence of the resulting doorway (time etc.) to ingress and egress is considered. The operating concept along multiple trajectories is tested in the virtual environment first, then on real car doors aiming at operating forces and directions.

In the presented design, process function (control, sensors) and component driven (door kinematics) understanding of the door system can be identified. In order to merge the different views functions and system elements are merged into one product model (Figure 6, left). This allows for the parallel and consistent detailing of both domains in the course of the further development. In order to handle the functional domain, the system domain and their interactions, a multi domain matrix (MDM [17]) is used that allows for single domain as well as for cross domain analysis and optimization of the product model [17].

The system elements from different disciplines like cameras, control algorithms and door kinematics are developed in simultaneous, not perfectly synchronized, processes of different duration. The correlation of the processes therefore has to be chronologically structured by several milestones and transparently reflected by an interdisciplinary process model that is linked to the product model.

In function driven process design the MDM-based product and process model are linked through the deliverables produced by the completion of work packages [18]. In order to fulfil a function or to realize a system element several deliverables, such as design drawings or test reports, have to be generated. There can be a direct (●) or an indirect (○) linkage between functions and deliverables (Figure 6, right). For every product design there is a logical – experience based – sequence of deliverables produced during development and production. Through the deliverables, the milestones are associated with functions and system elements which meet grown conditions in departments of different disciplines. In addition the linkage of product model and process model offers the possibility to easily trace impacts of changes of the product structure on the process structure.

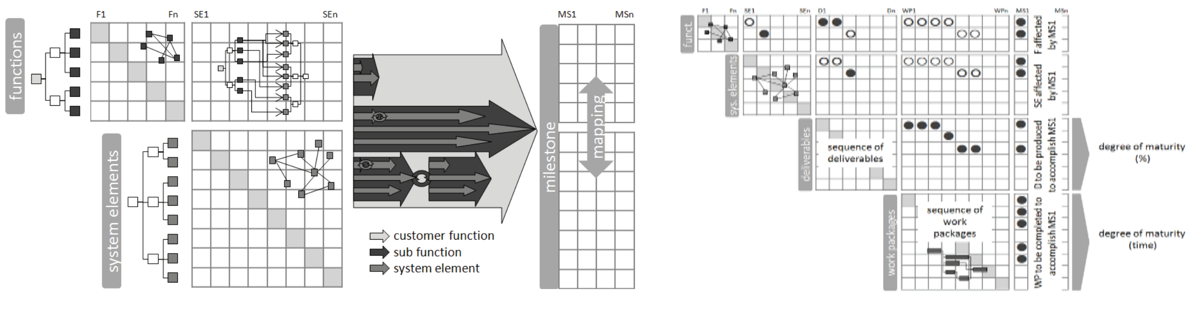

Figure 6: Symbolic illustration of the chronological correlation of processes [18].

Building up on the milestone system statements have to be made concerning the degree of maturity of a product – regarding both its functions and system elements. Therefor the work progress is associated with the deliverables produced and the work packages completed. As a consequence the degree of maturity can be linked to functions and system elements through the MDM. On the basis of the deliverables produced a percentage value can be given. Analyzing the progress of work packages completed a time measure can be stated (Figure 6, left).

DISCUSSION AND CONCLUSION

In this article a multidisciplinary development process of a new mechatronic door concept for improved and situation-dependent ingress/egress was presented. In the first step the reasons for occurring discomfort during ingress/egress were identified. Therefor the influences of different geometries of the car like door sill, seat height, or the A-pillar were studied using as well questionnaires as multi-body simulations. First analysis of the arm/shoulder movement show high correlation of both studies. Further on the analysis is devolved for a whole body movement to derive a model to generally objectify discomfort of movement.

The findings of the experiments so far, which give a rough clue of the optimal movement, were used to design new door kinematics. Two most effective concepts allowing multiple, situation-dependent door movements were presented. One concept uses an additional guide between door and car body to realise a displacement of the rotation axis. With its two degrees of freedom, the door can be opened situation-dependently. Major benefit of the second door concept, a sliding door, is the deblocking of the whole door cutout. With a pivoting and a translating function the door opens in two steps. Both designed door concepts fiercely increase the room in front of the ingress area. Further on the two concepts get actuated and controlled to enable safe and reliable operation. To generate new kinematics and speed up coming developments a kinematics development process was introduced. Prototypes of the design steps for motion input and kinematics synthesis are presented. Additionally various output methods like the software output, the link to the rapid prototyping process of 3D-printing and virtual prototyping were presented.

For the latter an experimental rig for a high fidelity haptic and visual simulation was implemented. Modelled as admittance, the rig can simulate forces and torques with respect to the interferences applied by the user.

To ensure a safe operation of the door two vision sensors with a large field of view were integrated. By means of these, a 3D-model of the workspace for ambiance information is generated. Obstacles, which could interfere with the door movement, can be extracted and incorporated by the controller of the door’s actuators. Out of the information provided by the camera system anthropometric data can be extracted and data for preadjustments can be collected.

In the next steps of development all proposed concepts have to be improved, their interaction has to be examined and finally they have to be integrated in one prototype.
In the field of process development an approach for function driven process modelling to support the development of mechatronic products was defined. It allows for a networked view on complex mechatronic products and their interdisciplinary design processes. Thereby it meets the requirements of grown corporate structures as it does not aim at changing but handling them. In the next step an approach for a tool based implementation will be developed. Special attention will be paid to the definition and design of the different disciplines’ views on the models and the hierarchy levels. This is supposed to enable an individual information search for different users and also avoid a surplus of information.

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