Towards a Generic Control System for Actuated Car Doors with Arbitrary Degrees of Freedom

Michael Strolz, Quirin Mühlbauer, Christian Scharfenberger, Georg Färber and Martin Buss

***Abstract*— Actuated car doors with more than one degree of freedom are a desirable means to boost the convenience of the access to cars. This paper outlines the problems connected with providing an intuitive, comfortable and safe operation of such doors. An advanced control system is proposed that overcomes these problems. First, a vision system for the monitoring of the workspace of the door is described. The data gathered is utilized by a collision avoidance method, which enables a safe operation of the car door. Second, a method for the support of the manual handling of the door is provided, which is based on predefined convenient paths for the specific kinematics of the door. Finally, the proposed control system is applied to a virtual car door, with successful results.**

I. INTRODUCTION

A broad variety of new door concepts is exhibited in automotive fairs every year. This points to the fact that conventional car doors with one rotational degree-of-freedom (DOF) do not provide an ideal solution for a convenient ingress. One of the key problems with such doors is that they cannot be fully opened due to obstacles like other cars, pillars or walls in many situations.

In recent years, this has led to a significant increase of cars with sliding doors which provide an improved convenience when compared to conventional doors. However, these doors have several drawbacks. An important one is that they are not fully accepted by customers in the area of sports or luxury cars because they often are associated with ordinary vans. This motivates the development of doors that combine the benefits of doors with one rotational DOF and doors with one translational DOF.

A. Motivation

In the past, several door concepts with more than one DOF have been developed. However, there has been no publication in literature that solves the problem of convenient and safe usage of such doors.

A car door with more than one DOF poses considerable design issues when compared to a conventional one. These depend on the kinematic and dynamic properties of the door and the shape of both door and vehicle. A detailed discussion of the design problems is beyond the scope of this paper, so just the most relevant ones are mentioned.

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Experiments on a Virtual Reality (VR) test bed showed that users did not find the operation of car doors with several DOFs (e.g. a pivotable sliding door) to be intuitive, and that they had problems to control it as well. Especially the dynamics of the links of the virtual doors led to a behavior that users were unable to fully anticipate. For this reason, we suggest the use of actuators and a controller. The controller can provide an intuitive and comfortable handling of the car door and thereby overcome the problems mentioned. This paves the way for using any number of actuated DOFs, which could be desirable in the future.

If a door is equipped with actuators, it is straightforward to use them for additional purposes. For instance, the actuation can be used to adapt the car door to meet the users' demands. This is a key advantage of an actuated car door in comparison to a conventional one as it allows an optimized behavior of the door for each individual user. However, the most important additional task of an actuated door might be to prevent collisions. This is especially true for a door with several DOFs, because many kinematic configurations may bear the possibility of self-collision (between door and car body) in addition to a collision with other objects. Hence, we suggest both a vision system for the detection of obstacles and a generic method to avoid collisions.

B. Related Work

Stereo vision and object recognition using vision systems is a well explored field, [1]–[5]. Solutions for collision avoidance can be found in [6], [7]. Furthermore, there exist numerous control algorithms for haptic interfaces [8] which an actuated car door indeed is. In addition, [9]–[11] deal with the estimation of the users' intention.

A few mechatronic systems that assist the movements of car doors have been developed by the automotive industry. Most of them are supervisory systems that only block the movement of the car door in case of a possible collision [12], [13], or provide an automated procedure for opening and closing the door [14], [15].

The contribution of this work is a control system which provides an intuitive, comfortable and safe operation of actuated car doors with more than one DOF. The paper begins with a description of the concept of such a control system. This is followed by a discussion of a vision system for the detection of obstacles and a method for the avoidance of collisions. After that, a method for the active support of the movement of the door is developed. Finally, the implementation on a VR test bed is described, and the results of a user study are discussed.

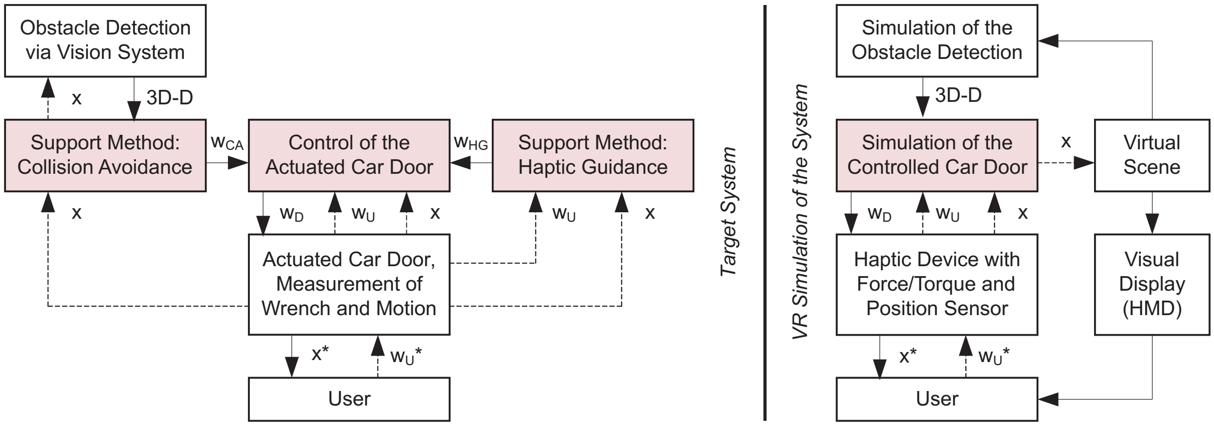

Fig. 1. Control system for actuated car doors with more than one DOF. Left: The target system, an actuated car door with methods for collision avoidance and haptic support. Right: A virtual reality simulation of the door and its control that allows for the rapid design and evaluation of the control of the door.

II. CONCEPT

The concept of the proposed control system is depicted in Fig. 1 on the left. Its core is an admittance control scheme with an inner closed-loop position controller. This scheme calculates appropriate values of the forces and torques for the actuators, $\mathbf{w}_D$. This calculation is based on a measurement of the interaction wrench (= forces and torques) between the user and the door, $\mathbf{w}_U^*$ (see [16]), and the current position and orientation of the door, $\mathbf{x}^*$. Both the dynamic and kinematic properties of the actuated car door can be influenced by choosing an appropriate admittance control law.

The behavior of the admittance controlled door can further be influenced by applying an additional *virtual* wrench $\mathbf{w}_v$ to the admittance. Details of this *active admittance control* are given in [17]. The wrench results in a change in the motion of the door and is thereby indirectly felt by the user. The virtual wrench thus affects both the actuated system and the user. It can be useful as a haptic support in many applications, ranging from giving only partial information to the user (via a small and temporary $\mathbf{w}_v$) to determining the motion of the system (by applying an $\mathbf{w}_v$ that is larger than $\mathbf{w}_{U_{max}}^*$).

As mentioned before, when moving a door with more than one DOF the user should be supported by both a collision avoidance and a haptic guidance method. We have implemented such methods, the former based on obstacle detection and the latter based on the measurements $\mathbf{w}_U$ and $\mathbf{x}$. While $\mathbf{w}_U$ and $\mathbf{x}$ can be obtained by conventional sensors, obstacle detection requires a sophisticated vision system, which itself may require the signal $\mathbf{x}$. These support methods calculate virtual wrenches $\mathbf{w}_{CA}$ and $\mathbf{w}_{HG}$ and send them to the controller, where they are added to the measured user wrench $\mathbf{w}_U$ and then applied to the admittance. This results in a collision-free motion $\mathbf{x}^*$ of the door which feels intuitive and comfortable to the user. Thus, by enhancing an admittance control scheme with support methods, the architecture of a generic control system for actuated car doors with an arbitrary DOF is described.

A VR simulation has been used for the rapid design and evaluation of the proposed control system. The core of this VR test bed is the simulation of the controlled car door which comprises an admittance control law representing the kinematic and dynamic properties of the door and the two support methods. The wrench $\mathbf{w}_{Adm} = \mathbf{w}_U + \mathbf{w}_{CA} + \mathbf{w}_{HG}$ leads to a motion $\mathbf{x}_{Adm}$ of the virtual door. This simulated motion is conveyed to the user via the haptic device by an appropriate actuation wrench $\mathbf{w}_D$ which is computed by a closed-loop position control scheme.

The obstacle detection technique is simulated based on a virtual scene which consists of a representation of a car with one movable door and its environment. This scene is graphically fed back to the user via a Head Mounted Display (HMD) so that a high degree of immersence is achieved. This guarantees that the developed control system is tested under realistic conditions and can therefore be directly applied to a real actuated car door without major changes.

III. VISION SYSTEM

Obstacle avoidance is a prerequisite for safe door opening. Sensors such as lidar or ultrasonic sensors can be utilized to detect obstacles around the car. These sensors allow for easy distance measurement and fast data acquisition. However, the detection area of an ultrasonic sensor is small and to detect the entire workspace of the door, a set of ultrasonic sensors would be essential. Conventional lidar sensors offer a large horizontal measuring (effective) range, but the corresponding vertical range is very small.

To overcome these limitations, two vision sensors with a large field of view are integrated in the car door so that the workspace can be mapped in its entirety. The cameras used have a resolution of 752 x 480 pixels with an aperture angle ranging to 130 degrees. Under the assumption that the obstacles are at a minimum distance of 50 cm from the car and therefore out of the blind area of the cameras, their distances from the door can be extracted using stereo vision. Fig. 2 illustrates the field of stereo vision in this application as well as the relation between the car coordinate system and the position and rotation of camera 2.

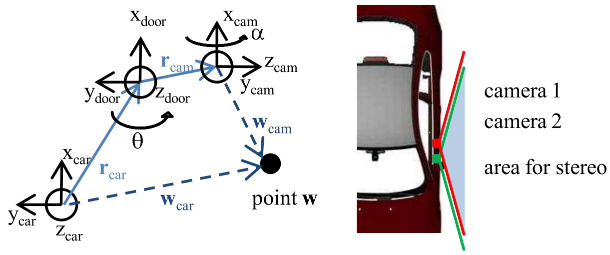

Fig. 2. Two cameras with a large field of view, integrated in the car door, detect the workspace. Distances from the car to obstacles are extracted using stereo vision with knowledge of the position of the cameras in relation to the car coordinate system.

The two cameras are intrinsically and extrinsically calibrated whereby camera 1 is calibrated to camera 2 based on a fixed distance δ between them. The actual position and orientation of the door is given by incremental sensors. The position of camera 2 in the car coordinate system is obtained using

$$\mathbf{T}^{\mathbf{ex}} = \mathrm{Trans}(\mathbf{r}_{car}) \cdot \mathrm{Rot}(z, \theta) \cdot \mathrm{Trans}(\mathbf{r}_{cam}) \cdot \mathrm{Rot}(x, \alpha) \quad (1)$$

and the inverse relation

$$(\mathbf{T}^{\mathbf{ex}})^{-1} = \mathrm{Rot}^{-1}(x, \alpha) \cdot \mathrm{Trans}(-\mathbf{r}_{cam}) \cdot \mathrm{Rot}^{-1}(z, \theta) \cdot \mathrm{Trans}(-\mathbf{r}_{car}) \quad (2)$$

where $\mathrm{Trans}(\mathbf{r}_{car})$ represents the translations of the car door and $\mathrm{Trans}(\mathbf{r}_{camX})$ the translation of the camera system in the car coordinate system $\mathbf{v} = [x_{car}, y_{car}, z_{car}]$. $\mathrm{Rot}(z, \theta)$ and $\mathrm{Rot}(x, \alpha)$ describe the rotation of the system. The camera rotation $\mathrm{Rot}(x, \alpha)$ is static while the rotation $\mathrm{Rot}(z, \theta)$ and translation $\mathrm{Trans}(\mathbf{r}_{car})$ depend on the door position.

The coordinates of each world point $\mathbf{p} = [X, Y, Z]$ can be determined using

$$\mathbf{w}_{cam} = (\mathbf{T}^{\mathbf{ex}})^{-1} \cdot \mathbf{w}_{cam} \quad (3)$$

The pixel coordinates of each point depending on the camera system are obtained using the calibration matrix

$$\mathbf{K} = \begin{pmatrix} f_u & s & u_0 \\ 0 & f_v & v_0 \\ 0 & 0 & 1 \end{pmatrix} \quad (4)$$

which is composed of the camera skew s, the focal lengths f_u and f_v, and the optical centers u_0 and v_0.

First, two images of the workspace are taken by the vision sensors. Thereby, we assume only static obstacles are present around the car door. These images are rectified using the calibrated distance as well as the positions of the cameras and the distortion model of the sensors given by their intrinsic calibration.

In the next step, distinctive features (feature points) of the image given by camera 2, such as corners or edges, are extracted using the pyramidal Lucas-Kanade feature tracker [1]–[3]. This feature tracker enables a fast detection and localisation of feature points at subpixels precision. The extracted feature points are recovered on the corresponding image given by camera 1. The pixel coordinates of successfully extracted feature points are stored in a feature point matrix and their disparity is determined.

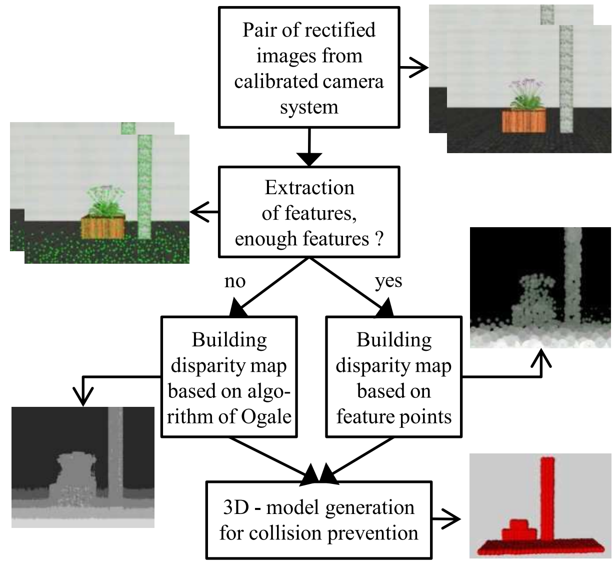

Fig. 3. Generating a disparity map with a pair of rectified images from a calibrated camera system using the Lucas-Kanade feature tracker or the stereo algorithms of Ogale. Based on this map, a 3D-model of the workspace for collision avoidance is provided, consisting of primitives (spheres).

In the simulated images, about 600 feature points in the region of interest are localized. However, if a sufficient number of feature points in the region of interest is not available due to a lack of distinctive features, then the stereo algorithms developed by Abhijit Ogale [4], [5] can be used to provide the disparity map of the workspace.

Based on the disparity of the feature points or the map obtained by the stereo algorithms, a 3D model of the workspace for collision avoidance is generated. This model, related to the car coordinate system, consists of primitive bounding boxes (spheres) with the center of each locating a feature point. The radius of each sphere varies with the predictable position of the point. If the position cannot be determined exactly in case of noise or other disturbances, then the radius of the spheres is increased. Fig. 3 illustrates the process of model generation using simulated images.

IV. Collision Avoidance

Based on the 3D data (3D-D) gathered by the vision system, a collision between the car door and other objects can be avoided by the actuation of the car door. Various methods can be used as the foundation for collision avoidance, ranging from simple collision detection to sophisticated path planning techniques. Collision detection is widely used in computer graphics and VR simulations. For a survey of collision detection see [18].

Due to the uncertainties of the vision system, the 3D-D varies both in the number and the size of the primitives bounding the objects in the workspace of the door. This impedes the use of planning techniques. Therefore, we concentrate on methods based on collision detection.

TABLE I

COLLISION DETECTION LIBRARIES: OVERVIEW AND BENCHMARK RESULTS

Library Properties				Benchmark: Maximum time consumption [ms]			
Name	Version	Algorithm	BV/BVH	Obstacle	CD only	CD & PD	CD & MD
Bullet	2.61	GJK (mod.)	AABB	Or. Cube	x	32.03	32.03
ColDet	1.1	Sep. Axis	OBB	Pyramid	24.19	x	x
ODE	0.9	Sep. Axis	AABB	Or. Cube	24.32	x	x
PQP	1.3	Sep. Axis	OBB, RSS	Or. Cube	32.15	x	33.61
QuickCD	1.0	Sep. Axis	k-DOP	Pyramid	>100	x	x
RAPID	2.01	Sep. Axis	OBB	Or. Cube	35.47	x	x
SOLID	3.5.6	GJK (mod.)	AABB	Or. Cube	19.48	24.65	21.64
SWIFT++	1.2	LC (mod.)	AABB	Or. Cube	56.31	x	98.27
V-Clip	1.0	LC (mod.)	OBB et al.	Or. Cube	82.15	x	82.15
V-COLLIDE	1.1	Sep. Axis	OBB	Or. Cube	>100	x	x

To achieve a high performance index for the collision avoidance system, collision detection has to be very efficient. Numerous comparisons both between collision detection algorithms and their implementations have been made, see e.g. [6], [7]. They all point out that the performance greatly depends on the respective scenario, e.g. the number, size, arrangement and representation of the objects.

Thus, we examine different collision detection libraries for a specific realistic car door scenario before developing a collision avoidance method.

A. Performance benchmark of Collision Detection Libraries

A variety of collision detection libraries (CDL) have been programmed in the recent years. Most of them are implementations of the Separating Axes Theorem, the GJK algorithm, or the Lin-Canny algorithm. Besides using different algorithms, they significantly differ in terms of the internal object representation: the bounding volumes (BV) and the bounding volume hierarchy (BVH).

An overview of relevant CDLs is given in Tab. I on the left side. All CDLs can be used to check whether 3D-objects intersect. Some of the CDLs can perform not only a collision detection (CD) between two or more objects, but can also compute the penetration depth (PD) and/or the minimal distance (MD) between them. The additional information that is provided by the PD and MD data are the location and the proximity between two objects. This information is very valuable for collision avoidance, because it allows for the direct calculation of an appropriate wrench $\mathbf{w}_{CA}$. The only library providing both PD and MD is SOLID [19].

To benchmark the CDLs, a scenario had to be defined that contains one or more objects in the workspace of the car door. The preconditions and assumptions for the overall collision avoidance were as follows:

- The position and orientation of the car door are known.
- The objects are static or moving slowly (maximum velocity: pedestrian speed).
- There is no object tracking. Only the low-level information (primitives) of the vision system is available.
- All current primitives (maximum number: 1000) computed by the vision system are provided to the CDL.

A quasi-static benchmark scenario accounting for these points has been defined, containing a bounding volume of the car door with 64 vertices, 10 oriented boxes that bound the left hand side of the car body and 100 primitives representing two objects: a cylindrical one (like a lamppost) and an asymmetric one (like a bush). Most CDLs do not support the use of spheres, so oriented cubes have been chosen instead.

Every CDL has been benchmarked using the defined scenario by performing 10,000 consecutive runs. The position and orientation of both the door and the objects were randomized each time. A Linux system with an Intel Pentium M 1.76 GHz and 512 MB RAM served as a test bed. The minimum, mean and maximum time of all runs was calculated and stored, see Tab. I on the right side.

The safety of the overall system is determined by the maximum time consumption that can occur, so in our case this is the most relevant factor. It turned out that SOLID outperformed all other libraries (both in maximum and mean time consumption). Besides the efficiency of the modified GJK algorithm relative to the defined scenario, a major reason for the fast execution of the single runs is due to the efficient way objects are handled by SOLID. One reason for the poor performance of other libraries results from their computational expensive scene building. The only other library that also showed a good performance and is not restricted to CD is Bullet [20]. In the future, Bullet might become an interesting alternative to SOLID, because it is a rapidly advancing Open Source project, while SOLID is no longer enhanced.

B. Collision Avoidance Method

The fast determination ($< 20ms$) of the distance between the car door and potential obstacles allows for a variety of different methods for avoiding a collision. For instance, methods with several consecutive CDL queries are possible.

In our scenario, the shortest achievable braking trajectory $\mathbf{x}_{bt}(t)$ which can be obtained by applying a wrench $\mathbf{w}_{CA}$ to the car door is of great importance for the collision avoidance. Particularly interesting is the overall time consumption $\mathbf{\Delta}t_{bt}$ of this trajectory and its final states $\mathbf{x}_{bt}(t_{End})$. These can be calculated if the following information is available:

- States and kinodynamic properties of the car door
- Parameters of the actuation and its control
- Time delay of the 3D-D calculation
- Time delay of the communication between the different modules

With knowledge of $\mathbf{x}_{bt}(t)$ and $\mathbf{x}_{bt}(t_{End})$, the convex hull of the movement of the braking door can be calculated using the 3D-model of the door. This calculation can be computational expensive. An alternative is the use of precomputed convex hulls of the moving door, which requires appropriate safety margins as well as a transformation according to the current door position and orientation. If in a first CD query no collision between the convex hull and the primitives is detected, the door can safely be stopped if necessary. In this case, a second CD query can be used to determine if the door is in danger of colliding with an obstacle. This can be done by defining an additional safety margin (several centimeters) and adding it either to the convex hull or to all of the primitives (which usually is less computational expensive). If the second CD query indicates no collision, the wrench $\mathbf{w}_{CA}$ of the collision avoidance is set to zero, else it is calculated to provide the maximum braking effect.

In case the first CD indicates that the door cannot be stopped safely by its actuation alone any more, two possibilities for the application of a wrench $\mathbf{w}_{CA}$ exist:

- $\mathbf{w}_{CA}$ that causes a collision-free motion of the door
- $\mathbf{w}_{CA}$ that diminishes the impact of the collision

The determination of the best option can be based on several parameters, including information about the door, its surrounding and the user. Note, that so far the significant influence of the user interaction on the collision avoidance of the car door has not been taken into account. It seems very promising to include the user into the collision avoidance, for example by giving him haptic clues representing the danger of collisions. Though, a discussion of these issues is beyond the scope of this paper.

V. ACTIVE HAPTIC SUPPORT

As pointed out, a car door which can be moved with several DOFs might not be intuitive to the user. Therefore, an active haptic support that can recognize the user's intent and assist his/her movements is essential. The most obvious approach is the use of different, predefined paths where the user can select the desired one. Furthermore, the user should have the possibility to move between those paths. Thus, the haptic support provided by an actuation wrench $\mathbf{w}_{HG}$ can be calculated using two separate operational modes:

- Static force field, which is applied when the user is following one of the predefined paths.
- Dynamic force field, which is applied when the user is moving between predefined paths.

For a suitable haptic support, the selection of a predefined path and a fluent movement between the paths have to be intuitive. Hence, the system has to gain knowledge about the users intent [10], [11], which can be performed based on the measurement of the user's movements, forces and torques.

A. Static Force Field

The static force field is created by a PD controller. For each predefined path, a force field is created. To support the user, the correct force field has to be selected. The force fields are weighted with the factor $\mathbf{g}$, which is computed using the Bayes' theorem [9]

$$P_k(\mathbf{x}_e|\mathbf{s}_k,\mathbf{x}_k) \propto P_{User}(\mathbf{s}_k|\mathbf{x}_e,\mathbf{x}_k)P_k(\mathbf{x}_e|\mathbf{x}_k) \qquad (5)$$

The position and orientation of the door handle at time k is denoted by $\mathbf{x_k}$, user signals by $\mathbf{s}_k$. A signal can be a force or torque applied by the user.

- $P_k(\mathbf{x}_e|\mathbf{x}_k)$ is the a priori distribution, based on the position and orientation of the door handle. It denotes the probability from the controllers point of view, that a user aims a configuration $\mathbf{x}_e$ for a given $\mathbf{x}_k$. User signals and previous positions like $\mathbf{x_{k-1}}$ and are not taken into account.
- $P_{User}(\mathbf{s}_k|\mathbf{x}_e,\mathbf{x}_k)$ denotes the model of the user. It denotes the probability to observe the user signals $\mathbf{s}_k$, if the user wants to approach the configuration $\mathbf{x}_e$. $\mathbf{x}_k$ is taken into account for this calculation.
- $P_k(\mathbf{x}_e|\mathbf{s}_k,\mathbf{x}_k)$ is the a posteriori distribution over all possible intentions of the user, after all user signals $\mathbf{s}_k$ have been taken into account.

After the probabilities for each of the predefined path have been computed, the weight factors are calculated based on these probabilities: high probabilities lead to a high weight, and low probabilities to a low weight for the corresponding force field.

B. Dynamic Force Field

The computation of weighting factors is sufficient for the selection of a predefined path, but once one of these paths has been selected the algorithm can not be used to leave it and to select another predefined path. To allow the interchange between two or more paths, a dynamic force field leading from one path to another has to be created. To compute the intention of the user, a probability is assigned to each predefined path. This probability is described using a Gaussian distribution and depends on a distance measurement between the user and the path. For the distance measurement, the Euclidean distance between the two Cartesian points and the Euclidean distance between the two quaternions [21] describing the rotations is used. Quaternions are used to represent the orientation as they provide several advantages like exhibiting no singularities in comparison to other representations like Euler angles. The intention recognition uses the probability and the movement of the door handle to estimate the aim of the user.

Fig. 4 shows how a possible target point $\mathbf{z}_i$ is computed. The distance d_i between the position $\mathbf{x}$ of the user and a predefined path i is calculated, and a search window ($k_{S,i}$ to $k_{E,i}$) whose size corresponds to d_i is created on the path i. This can be seen in Fig. 4, where in (a) the window is larger than in (b). The direction of the user's movement $\mathbf{m}$ is used to compute the target $\mathbf{z}_i$, which has to be located inside the

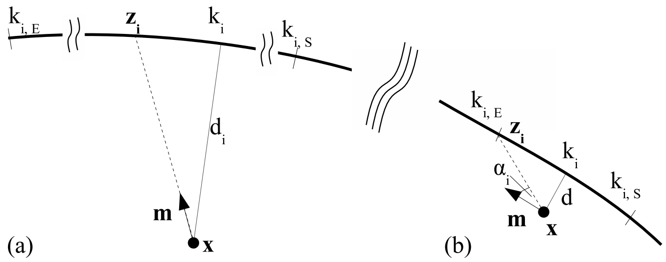

Fig. 4. Possible target points for a user approaching a predefined path. In (a) the user is moving towards a path, while in (b) the users movement is parallel to a path.

search window. In 4 (b), the movement is parallel to the path and consequently leads to a point outside the window. The resulting computed target point will be located inside, so that the user will finally reach the path.

For each of the predefined paths, one possible target point is computed. In a next step, an algorithm based on a point rating system is used to differ between the possible targets and estimate the users' desired target:

- If the user is moving towards a point, this point will be rewarded. Else, it will be punished.
- The closest point and the point whose distance is decreasing the quickest will get an extra reward.

After all possible target points have been rewarded or punished, the point with the best rating is selected as target and a force field leading to the point is computed. This dynamic force field is computed using the same algorithm as for a static force field.

VI. Application to a VR test bed

As a wide variety of control algorithms can be tested without changing a hardware setup, an experimental VR test bed is well suited for the development and testing of methods and algorithms for a car door with arbitrary DOFs. This section describes a VR test bed where any kinematic configuration of the door can be simulated and a control algorithm to control such a car door. Furthermore, some preliminary results of an explorative case study are shown.

A. Experimental Setup

The ViSHARD10 [8] was used as haptic interface of the VR test bed. Its large, singularity-free workspace makes it ideally suited to simulate large mechanisms which a car door is. The end-effector serves as haptic interaction port by simulating the car door handle. Thus, the terms door handle and end-effector are used synonymously. The car and the car door with its corresponding movements is visualized by a projector. For an improved immersion, an HMD with a head tracking system to show the correct perspective can be used optionally. Fig. 5 shows the whole experimental setup.

To control the ViSHARD10, we use an admittance control algorithm [22]. This algorithm uses input forces and torques to compute the target position and orientation of the end-effector and consequently the necessary motor torques. The user holds the door handle, creating the necessary forces and torques. Hence, the haptic support algorithm for the car door needs to compute forces and torques, which are impressed to the user. As inputs, we use the position and orientation of the end-effector.

Fig. 5. Virtual Reality test bed in operation. The haptic device (right) is simulating the car door, visual feedback is provided by a projector (left).

The following section describes the control scheme of the haptic support. As mentioned before, the target position and orientation $\mathbf{x}$ of the door handle, as well as the wrench $\mathbf{w}_U$ are used by the haptic support to estimate the users intention. Hence, the intention recognition computes the necessary parameters for the creation of the force fields, as well as gains $\mathbf{g}$ to weight the resulting force fields and a virtual damping to create virtual walls surrounding the workspace. The supporting wrench $\mathbf{w}_{HG}$ is then computed by weighting the different force fields. In order to use the haptic support algorithm for a real car door or any other simulation, $\mathbf{w}_{HG}$ may serve as an input to other controllers as well.

B. Results

An explorative case study with human subjects is an easy way to obtain knowledge about the acceptance of the simulated novel car door. To obtain preliminary results, a study with 10 test subjects was conducted. The goal was only to get a first impression about the acceptance of the virtual car door and its control and to gain helpful information for further improvements. Towards this, a questionnaire with both discrete measures ('good', 'quite good', 'quite bad' and 'bad) and open questions was developed.

The results of the case study are very promising, as can be seen in the left-most diagram of Fig. 6. Each subject judged the system as a whole as 'good' or 'quite good'. Furthermore, the usability of the system was also evaluated to be fair. The main objection of some subjects was the movement of the door between the predefined paths, which was where most of the test subjects encountered some difficulties (see Fig. 6, middle and right diagrams).

In an additional test, different parameter settings were compared. Particularly noticeable was a difference between male and female test subjects. Males preferred control pa-

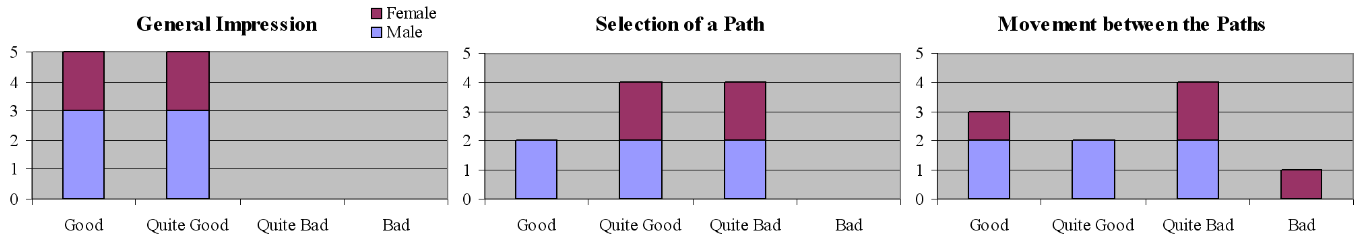

Fig. 6. Selected results of the explorative case study

rameters that yield a higher stiffness, whereas females preferred the opposite. Although the experiments were confined to 10 subjects, this is a strong indication that an individual setting of the control parameters of an actuated car door can significantly increase user acceptance.

VII. CONCLUSIONS

In this paper, the motivation to use car doors with more than one DOF and the inherent problems that have to be overcome are discussed. It is shown that these doors should be equipped with actuators. A concept for the control of such doors is outlined, which comprises of methods to support the user. The haptic guidance method allows for an intuitive handling of the door, and the collision avoidance method counteracts possible collisions between the door and other objects using a vision system.

The principles of the vision system are presented. Distances from quasi-static obstacles to the car are determined using stereo vision. The proposed algorithm was developed in a simulated environment. In case of the implementation of the stereo algorithm given by Abhijit Ogale and the use of the Lucas-Kanade feature tracker, this technology can be re-used in a real environment and under real conditions. The output of the vision system are primitives that bound the obstacles. These are used to check whether the moving car door is about to collide. If this is the case, an appropriate actuation wrench is applied to the car door, which prevents the collision or at least diminishes its impact.

To successfully provide a haptic support, the intention of the user has to be estimated. An algorithm capable of analyzing the user's intent was developed. Furthermore, we presented a VR test bed, which can simulate any car door and which represents a very efficient tool to implement and test control algorithms for them.

To validate the haptic support and the acceptance of the overall simulation of the actuated car door, an explorative case study has been conducted. The results clearly indicate that the proposed control system shows promise.

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