

Towards a soft robotic, haptic feedback seat for autonomy level transitions in highly-automated vehicles*

Jan Peters¹, Bani Anvari², Annika Raatz¹ and Helge A. Wurdemann³

Abstract—Self-driving autonomous cars are one of the most significant transforming technologies in the next decades. However, before having fully autonomous vehicles that can complete end-to-end journeys, there will be the need to give back control to the human driver in certain situations. These human-robot handovers lead to safety risks, especially in scenarios where the driver’s awareness is not focused on the traffic situation. Here, we present a concept for a soft robotic driving seat, that supports with the autonomy transition to hand over the driving control safely back to the driver in a highly-automated vehicle. Instead of using visual or auditory signals, the haptic seat is able to give a more intuitive and less distracting feedback about the actual driving situation and, by that, increasing the driver’s situational awareness in critical situations. Twenty-one subjects participated in seven driving scenarios in a simulator, each with a different take-over request modality (audio or tactile). The auditory stimuli were presented via headphones in the simulator and the haptic feedback via twelve soft pneumatic actuators in the bottom and upper side bolsters of the driving seat. The results showed that the participants preferred the haptic feedback over the audio signals. Moreover, our results showed high usability and acceptance of the developed system.

I. INTRODUCTION

According to the most optimistic predictions, the first commercially available fully autonomous cars are expected in 2040 offering the consumer a full end-to-end journey [1]. These self-driving vehicles will be equipped with technology allowing autonomy Level 5 in which there is no interference required by the human. In the race towards the first fully autonomous car, the majority of cars will be equipped with technology that allows Level 3 or 4 autonomy over the next two decades. These semi-autonomous cars might be able to transport the driver autonomously on sections of a journey. However, the driver is required to take control occasionally between different levels of autonomy when required to complete an end-to-end journey. These handovers between the car and the driver cause safety concerns, as the driver might not be fully aware of the surrounding situation and the enabled autonomy features instantly [2].

This paper proposes a new interface design for highly-automated cars called iSeat (Figure 1). This system is funda-

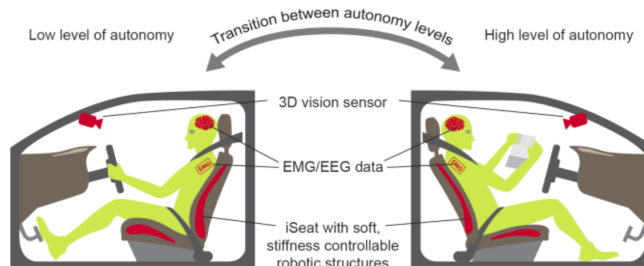


Fig. 1. Proposed iSeat with integrated soft, stiffness controllable robotic structures. Pressure data will be fused with EMG/EEG and vision information to define personalised haptic feedback using iSeat to allow safe transitions between different levels of autonomy.

mentally different compared to current systems using visual or auditory indications; our system comprises an intelligent driver seat acting as a co-pilot measuring the current mental and physical engagement of the driver and allowing safe and coordinated autonomy level transitions. Of particular significance is the driver seat made of robotic structures serving the feedback purpose as well as providing monitoring capabilities through direct contact with the human. iSeat sensing information will be fused with multi-modal sensing data from electrical activity produced by skeletal muscles (Electromyography (EMG)) and in the driver’s brain (Electroencephalography (EEG)), and input from vision cameras regarding the driver’s posture and the point of gaze. This real-time knowledge will be classified through machine learning in terms of the drivers’ awareness. Personalized feedback will be provided (i.e., tactile sensation, stiffness feedback, change of the driver seat ergonomics/comfort) to support the driver so that safe, timely, effective, and intuitive transitions between different levels of autonomy can be completed.

II. DESIGN, FABRICATION AND CHARACTERISATION OF THE SOFT PNEUMATIC ACTUATORS FOR HAPTIC FEEDBACK

A. Manufacturing the soft pneumatic actuator

Figure 2 shows the design of the soft actuator, composed of several layers of silicone (Smooth On, Ecoflex 00-30), rectified with a two-way stretch textile which reduces the radial balloon phenomenon resulting in one-directional elongation only. The design is inspired by our previous work [4] and has been adapted here to the space requirements in the driver seat. An inextensible fabric (Jackson’s Art, 43T Polyester Mesh) is used to reduce the bulge effect on the upper and lower surfaces of the actuator during operation. An

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¹J. Peters and A. Raatz are with the Institute of Assembly Technology, Leibniz University Hannover, Germany. peters@match.uni-hannover.de

²B. Anvari is with the Department of Civil, Environmental and Geomatic Engineering, University College London, UK.

³H.A. Wurdemann is with the Department of Mechanical Engineering, University College London, UK. h.wurdemann@ucl.ac.uk

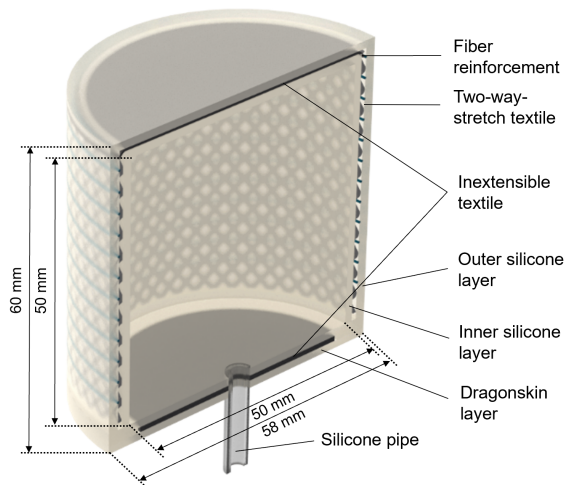


Fig. 2. The silicone-based soft actuator for the side bolsters has a cylindrical shape with a diameter of 58 mm and height of 70 mm. 2-way stretch textile and an inextensible fiber are embedded between silicone layers in the wall.

additional layer of a stiffer silicone (Smooth On, Dragonskin 30) increases the shape stability at the bottom part. An inlet at the bottom provides the soft actuator with air pressure.

Each of the silicone parts is produced using PLA moulds. The first layer of the main body is composed of a cylindrical 53 mm wide hollowed silicone chamber (Ecoflex 00-30) with an inner diameter and height of 50 mm. An inextensible fiber is wrapped around the fabric to reduce radial expansion of the actuator but allow axial elongation. Additionally, to increase the stability of the actuator against shear forces and to suppress evasive movements in radial direction, the outer wall of the chamber is lined with a two-way stretch fabric. A second hollow cylindrical silicone chamber was then moulded with an inner diameter of 58 mm and height of 64 mm.

The base of the actuator was constructed from two layers of silicone plates (55 mm diameter, 6 mm thickness) and fortified with an inextensible fabric between the two silicone layers. Each of the base layer components was fabricated with a hole in the centre which was reserved for the placement of the pneumatic pipe (3 mm inner diameter, 5 mm). Finally, the silicone chamber and hydraulic silicone pipe were sealed together using silicone glue.

III. THE SOFT ROBOTIC SEAT

Our proposed concept, as shown in Figure 3 is based on a Landrover Discovery Sport SE driver seat. It includes two actuation areas with different actuators arranged in signal patterns for complex signal transmission to the driver during the handover process. The seat has a 2 mm genuine leather seat cover with 40 mm to 100 mm foam underneath. Twelve soft actuators are placed in the foam, directly under the leather seat cover of the upper and lower side bolsters of the seat according to Fig. 3. The side bolsters offer space for the actuators and are less pressurised through the weight of the driver, leading to a lower actuation pressure. Additionally,

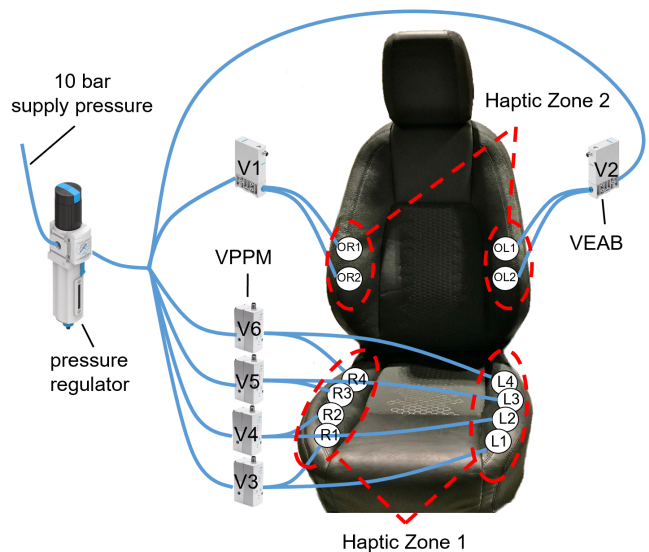


Fig. 3. Each side bolster is equipped with four actuators. Each pair of actuators can be controlled individually by proportional pressure regulators, allowing complex haptic signal patterns to be generated.

signals in the side cushions are perceived as more pleasant compared to signals in the bottom of the seat [5].

A. Haptic Feedback Zones

In order to provide directional signals, two haptic feedback areas are defined. Haptic zone 1 is used to transmit signals along the direction of travel (x-direction), and haptic zone 2 is used to distinguish between the left and right side of the driver (y-direction). The selected positions of the actuators in the seat and the haptic are also shown in Fig. 3. There are eight actuators in the bottom side bolsters, four on each side. Since the signals transmitted in haptic zone 1 can be symmetrical to the x-axis, the actuators lying at the same height in x-direction are combined and operated with one valve. In haptic zone 2, i.e. signals that refer to the left or right side of the vehicle (y-direction) the actuators OR1 and OR2, as well as OL1 and OL2, are combined with one valve each. The distance between the centres of the actuators of 60 mm was chosen taking into account the human sense of touch in the respective areas. The two-point contact threshold which determines the spatial resolution is 40 mm for the legs and 45 mm for the back [6].

B. Peripherals

The actuators are controlled by a programmable logic controller (PLC) (Conelcom GmbH, Controllino Maxi Automation) that is connected by I2C-bus and an analog output module to the two different kinds of valves. The lower actuators (R1-4, L1-4) are operated by proportional pressure regulators of the type VPPM (Festo, VPPM-6L-L-1-G18-0L2H-V1P-S1) for fast and dynamic pressurisation, while the actuators in the upper part of the seat (OR1, OR2, OL1, OL2) are actuated with smaller proportional pressure regulators (Festo, VEAB-L-26-D2-Q4-V1-1R1). The different signal patterns are stored as modes on the PLC and can be activated

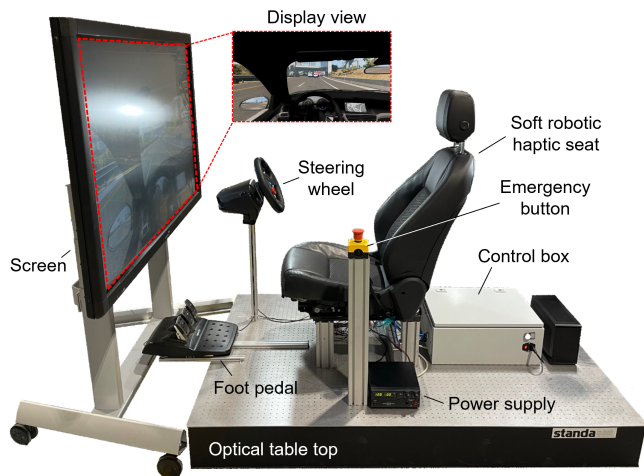


Fig. 4. Our robotic haptic seat, its control box and power supply are arranged in front of a screen on a Honeycomb optical tabletop. A steering wheel and foot pedal complete the driving simulator setup.

on the control-PC. Besides that, the PLC is handling user input like the emergency and reset button with interrupt service routines. The pneumatic and electronic parts are located in a dedicated control box.

IV. EXPERIMENTAL SETUP, PROTOCOL, RESULTS AND DISCUSSION

In Section IV-A, the experimental setup is described which includes a fundamental driving simulator with the soft robotic haptic driver seat at its centre. Three experiments have been conducted to assess the driver acceptance (usefulness and satisfaction) and haptic seat's usability (see Section IV-B). Therefore, driving scenarios were created that are described in Section IV-C. The results and discussion of these experiments are given in Section V and VI.

A. Description of the driving simulator - experimental setup

Our soft robotic haptic seat is core to the driving simulator located in front of a screen, as shown in Figure 4. The seat, including its control box and power supply are mounted on a Honeycomb optical tabletop by Standa. A steering wheel and foot pedal (Logitech, G29 Driving Force) are placed in front of the driving seat. It is important to mention that the seat, screen as well as steering wheel and foot pedal can be adjusted in horizontal and vertical position to accommodate the preferred driving position of all participants providing an immersive driving experience.

B. Experimental protocol

Experiment 1: All participants are introduced to the haptic feedback they will experience during defined driving scenarios. First, the four soft actuators in the shoulder area of the seat back cushion OR1, OR2, OL1 and OL2 (see Figure 3) are activated: A pressure of 200mbar is simultaneously applied four times for 1 s. Then, the pressure in each of the eight soft actuators in the seat cushion (R1-R4 and L1-L4) is increased to 200mbar over a duration of 10s. In addition, actuator series on the left and right side are eight times

simultaneously actuated in a wavelike pattern over a period of 4.8s, that is also used for Experiments 2 and 3.

Experiment 2: Participants are informed that they will experience a set of driving scenarios (as explained in Section IV-C) sitting on the driving seat in a car with Level-2 autonomy, i.e., the vehicle has lane-keeping and cruise control ability. The car will be in Level-2 autonomy at the start of the driving scenarios. The participants are then instructed to take over full control, i.e., change the autonomy to Level 0, when an acoustic signal alerts them to do so.

Experiment 3: The participants are part of another five driving scenarios. Again, the vehicle will start in Level-2 autonomy. When the haptic driving seat alerts the participant through the wavelike pattern as experienced in Experiment 1, they are asked to take over control through operating the steering wheel and foot pedal.

Through a set of questionnaires, the driver acceptance (usefulness and satisfaction) and haptic seat's usability is assessed and evaluated by the participants. Based on the assessment procedure in [7], the driver acceptance of our new haptic seat is explored. The nine questions of the procedure are asked at the beginning of the study as a before-measurement and at the end of the study as a post-measurement. In this way, differences in expected usefulness and satisfaction and actual perceived usefulness and satisfaction are determined. The usability is measured through the commonly used usability scale by John Brooke [8].

C. Driving scenarios

The driving scenarios used for the described experiments are recorded with the simulation software Beam.NG on the simulation PC (AMD Ryzen 5 3600, Radeon RX5700 XT) in 1080p Full HD. To record the driving scenarios, various vehicles such as cars, buses and trucks are placed on at least two-lane motorways to represent, for example, a traffic jam, an accident, or other obstacles on the road. The driving scenarios are recorded in the interior view of an automatic car whose instrument panel and steering wheel fit well with the steering wheel of the driving simulator.

V. EXPERIMENTAL RESULTS

In Section V-A, the study collective is described, followed by detailed experimental results regarding the acceptance (Section V-B) of the system based on the experimental procedure introduced by Laan et al. [7].

A. Participants

The twenty-one participants (8 female, 13 male) in the study are employees and students of the Institute of Assembly Technology at Leibniz University Hanover. The prerequisite for participation is an age of at least 18 years and possession of a driving licence. The height of the test persons is between 160cm and 200cm (M=178.6cm, SD=10.1cm) with a weight of 55kg to 115kg (M=72.9kg, SD=13.8kg). The length of time the participants have held a driving licence is between 5 and 24 years (M=11.0 years, SD=5.2 years).

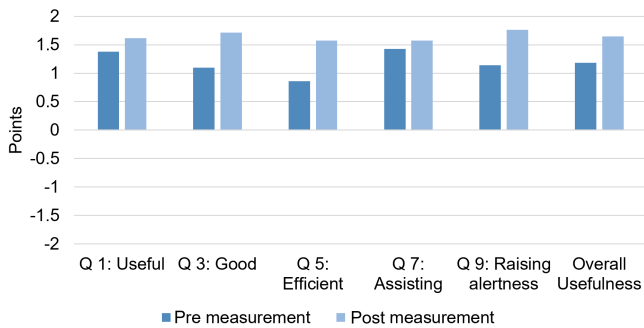


Fig. 5. Results with regards to the usefulness of the haptic seat before and after the participants' experience of the driving scenarios. Participants rated each question based on a Likert scale from -2 to 2 .

The participants had to confirm that they would not benefit from the study before it started.

B. User Acceptance of the Haptic Driver Seat

The results with regards to the acceptance of the haptic feedback system are shown in Figs. 5 and 6. The dark blue bars summarise the feedback before and the light blue bars the results after experiencing the scenarios. Participants rated each question based on a Likert scale from -2 to 2 .

The usefulness results of the haptic feedback system achieve an average of 1.19 points. The largest value for the pre-measurement has been returned for Question 1 resulting in 1.4 points ($s = 0.91$ points). On the other hand, the lowest value is measured for Question 5, assessing the perceived efficiency of the system. 0.93 points with a standard deviation of 0.96 were determined here.

After participating in the scenarios, the average score achieved 1.56 points. Here, Question 9 returned the largest points (1.67 points, $s = 0.62$ points), asking participants to rate the alertness of the haptic feedback seat. Results for the system's ability to assist resulted in the lowest points (1.40 points, $s = 0.63$ points).

Comparing the pre- and post-measurements, one can observe an increase of 31.1% on average. The largest increase has Question 3 with a total of 60% , whereas Question 7 shows only a minimal difference between the pre- and post-

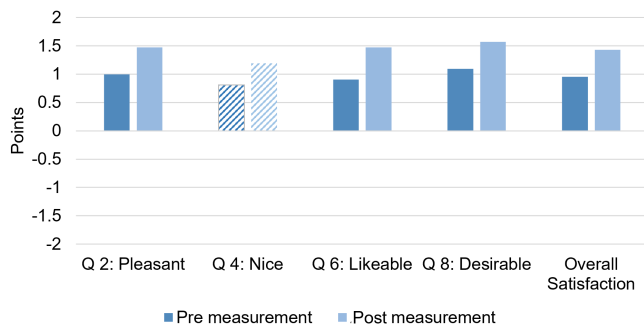


Fig. 6. Results with regards to the satisfaction of the haptic seat before and after the participants' experience of the driving scenarios. Participants rated each question based on a Likert scale from -2 to 2 .

measurements. However, it is worth noting that the standard deviation decreases from 0.96 to 0.63 points.

The results for the satisfaction of the haptic feedback system are shown in Fig. 6 achieving an average of 0.89 points in the pre-assessment. The largest points are returned by Question 8 (1.07 points with $s = 0.80$ points), the lowest score has Question 6 (0.67 points with $s = 0.72$ points).

Looking into the result after the participants experienced the haptic seat during the scenarios, the average rating is 1.4 points. Again, the result of Question 8 scores highest ($M = 1.47$ points, $s = 0.74$ points). Question 2 returned the lowest result with 1.33 points ($s = 0.82$ points).

An average of 57.5% increase between the pre- and post-measurements can be observed. Here, Question 6, which assesses the likeability of the system, has the largest increase with 110% . The smallest increase of 37.5% is determined for Question 4.

VI. CONCLUSIONS

Our iSeat system is fundamentally different from currently available feedback systems in highly automated vehicles. The combination of physiological and behavioural sensing systems, machine learning, haptics, and robotics can result in bi-directional human-machine cooperation that is safe, intuitive, and effective. In this paper, we presented our soft actuators to create haptic feedback areas in a driver seat, providing the driver with tactile feedback for a safe autonomy transition from the highly automated vehicle to the driver. Initial experimental results show the capabilities of the created actuator assessing the user acceptance through subject participation. The next steps of our project include the integration of more actuators, the combination of the sensor data (i.e., EEG and EMG) with machine learning, and finally experiments in a driving simulator with a larger number of participants to understand the overall iSeat concept.

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