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研究課題名（和文） Driver-automation mutual adaptation: modeling, design, and evaluation of haptic interface for cooperative driving tasks

研究課題名（英文） Driver-automation mutual adaptation: modeling, design, and evaluation of haptic interface for cooperative driving tasks

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研究成果の概要（和文）：この研究は、運転手と自動化の相互適応、および高度な自動運転体験のための触覚共有制御システムの開発に焦点を当てています。プロジェクトの初めに、運転手の行動を高精度で横方向制御モデルが確立されました。その後、運転手が介入できる共有制御を含むステアリングアシスタンスシステムが開発されました。このシステムは、車両がフェイルセーフ動作を開始する際の運転手の介入要求を考慮し、運転手の制御可能性に基づいた共有制御を開発しています。さらに、新しいドライビングシミュレータの研究により、更新された信頼値を持つ相互適応共有制御システムがテストされ、車線維持性能とユーザー満足度の向上が示されました。

研究成果の学術的意義や社会的意義
My research provides insights on understanding how driver interacts with haptic shared control system. Moreover, by designing a shared control system, my research helps to raise people’s motivation and ability to move that would expand their life space by improving driving safety and comfort.

研究成果の概要（英文）：This research focuses on driver-automation mutual adaptation and the development of haptic shared control systems for enhanced automated driving experiences. At the beginning of the project, a robust lateral control model for human drivers was established, demonstrating superior accuracy in identifying driver behavior. After that, A steering assistance system involving a shared control strategy was developed for driver override in automated vehicles. The system considers the potential driver demand for override when the vehicle initiates a fail-safe maneuver. A shared control strategy based on driver controllability is adopted to smoothly transfer driving authority when the vehicle is out of danger. Furthermore, novel driving simulator studies were conducted to test mutual adaptive shared control systems with updated trust values, showcasing improvements in lane-keeping performance and user satisfaction.

研究分野： Human-Machine Interaction

キーワード： HMI　Automated driving　Machine learning　Intelligent vehicles　Driver behavior modeling

１．研究開始当初の背景

The development of automation is advancing rapidly, but it doesn't mean humans will be replaced. Instead, humans are increasingly required to interact with automation in various complex systems such as aircraft, automobiles, manufacturing plants, homes, and hospitals. This field of study, known as human-automation interaction, covers taxonomies and qualitative models, analysis of automation-related accidents, adaptive automation design, and social, political, and ethical concerns. Adaptive automation, proposed to enhance human-automation cooperation, involves dynamic control shifting between humans and machines based on factors like workload, performance, and environmental conditions. This control shifting can happen through sharing or trading control, where either the human or automation system takes responsibility for functions, or they collaborate simultaneously.

Automated driving, a major focus, necessitates understanding and improving driver-automation interaction for real-world driving scenarios. To prevent confusion and ensure user-friendly designs across vehicle models, interfaces should be intuitive and have a high level of consistency. Haptic shared control, allowing drivers to feel and interact with automation through physical feedback, has been explored as an effective approach, akin to the horse-rider relationship where mutual learning and adaptation occur. Hence, this research proposal aims to investigate and model driver-automation mutual adaptation, aiming to design a mutually adaptive shared control system for cooperative driving tasks.

２．研究の目的

This research aims to investigate and model driver-automation mutual adaptation, aiming to design a mutually adaptive shared control system for cooperative driving tasks.

(1) Understand and model driver adaptive behavior under haptic shared control
(2) Propose a fail-safe system involving shared control strategy with adaption to driver override behavior
(3) Propose a novel data-driven shared control paradigm based on mutual adaption for system with unknown dynamics

３．研究の方法

A framework for driver-automation shared control with mutual adaptation is depicted in Figure 1. In a driving task, the driver primarily relies on visual perception, cognitive decision-making, and arm movements to control the steering wheel. Meanwhile, the automation system (i.e., the haptic guidance steering system, which includes sensors, a controller, and an actuator, as shown in the figure) provides assistive torque on the steering wheel.

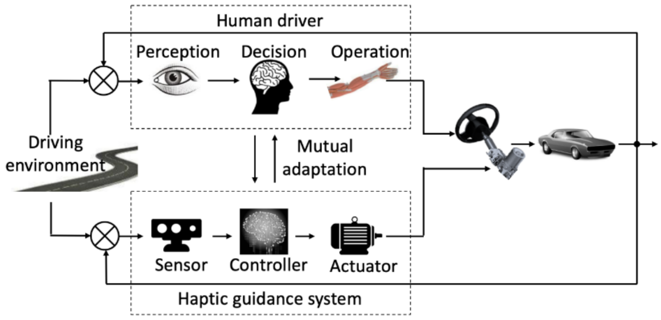


Figure 1. Schematic diagram of shared control

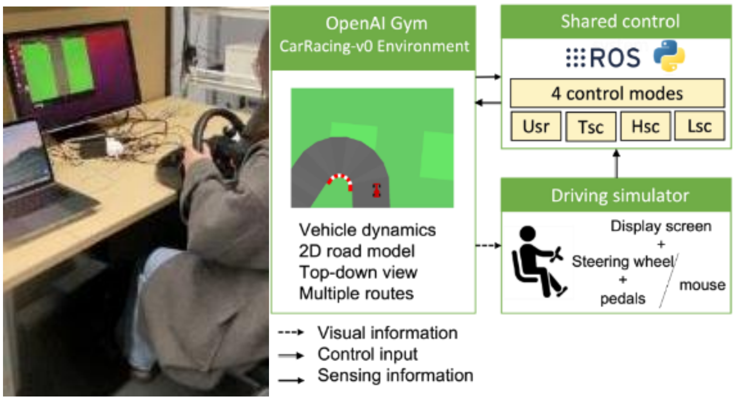


Figure 2. The desktop driving simulator and settings.

Our experiment was conducted using a driving simulator with a Logitech Driving Force GT steering wheel, along with throttle and brake pedals, as shown in Figure 2. Regarding the specific settings of the external input device, the steering wheel has a rotation angle range of 900 degrees. The resistance and gain of the steering wheel can be set from 0 to 100. The resistance value adjusts the effort required to turn the steering wheel, while the gain value adjusts the strength of the force feedback effects. In the experiment, the resistance was set to 15 and the gain was set to 80 using pyLinuxWheel, a graphical program in GTK3 for configuring Logitech steering wheels in Linux.

Our experiments were also conducted in a high-fidelity driving simulator equipped with an actual haptic shared control system, a 140° field-of-view screen, a moving platform, a steering wheel, and pedals for braking and acceleration, as shown in Figure 3. The moving platform, which has six degrees of freedom, was used to simulate the experience of driving on an actual road. The brake and accelerator pedals were used to control the longitudinal speed of the simulated vehicles.

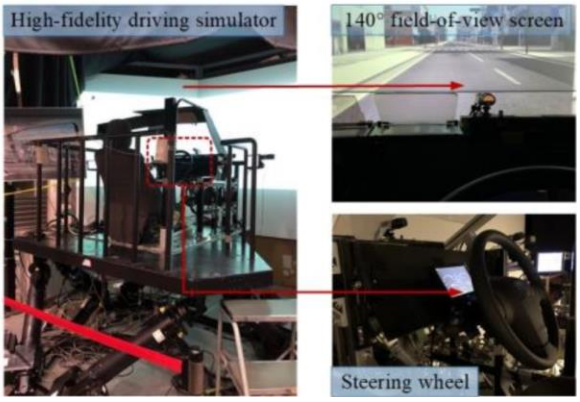


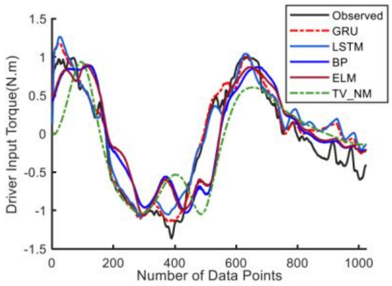
Figure 3. The high-fidelity driving simulator

４．研究成果

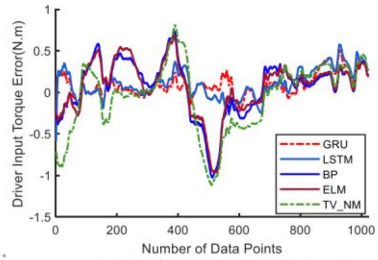
(1) Driver modelling to predict distracted driver behavior under shared control

To understand driver adaptive behavior under haptic shared control, a gated recurrent unit (GRU) network was developed to model the lateral control behavior of distracted drivers during driving. Eighteen participants, with an average age of 23.5 years, were recruited for the experiments. All participants held a Japanese driver's license and had an average driving experience of 2.7 years. The experiments were approved by the Office for Life Science Research Ethics and Safety at The University of Tokyo. Each participant performed a double lane change driving task with 3.6-meter-wide lanes.

Four modeling methods were used as benchmarks to evaluate the performance of the GRU network. These benchmarks included a state-of-the-art LSTM network, a backpropagation (BP) network, an extreme learning machine (ELM), and a traditional two-point visual model with neuromuscular dynamics (TV_NM). Data from the high-fidelity driving simulator experiments was divided into a training set and a test set: data from twelve participants was used for training, while data from the remaining six participants was used for testing the GRU, LSTM, BP, and ELM networks.



(a) Driver input torque by Driver 17.



(b) Driver input torque error by Driver 17.

Figure. 4. An example of identified results

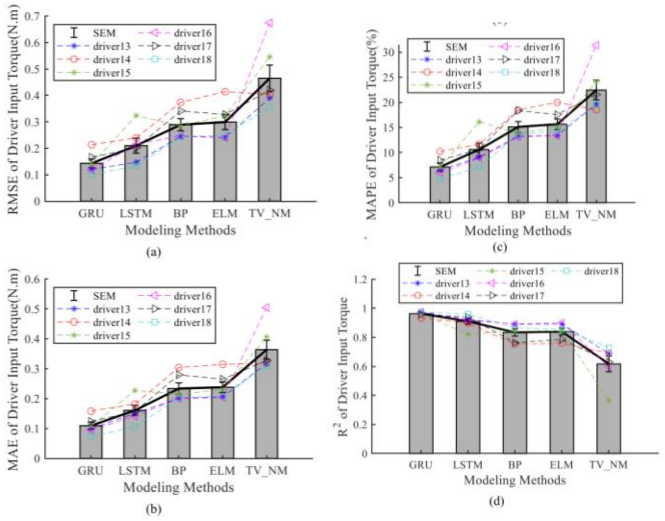


Figure 5. Identified results of driver input torque

The results indicate that the GRU network has superior identification accuracy compared to the LSTM network, BP network, ELM, and TV_NM method. Figure 4 illustrates the identification results of input torque for Driver 17 under the HGT-Constant condition as an example. The proposed GRU network significantly reduced the identification error compared to the LSTM, BP, and ELM networks.

Figure 5 presents the RMSE, MAE, MPAE, and R^2 of the driver input torque. The GRU network outperforms the BP network, ELM network, and TV_NM modeling methods across all these metrics. Additionally, both the GRU and LSTM networks perform significantly better than the BP network, ELM network, and TV_NM model. While the BP and ELM networks show a notable tendency to perform better than the TV_NM model, there is no significant difference between the BP and ELM modeling methods in terms of RMSE, MAE, MPAE, and R^2.

(2) Developing a fail-safe system involving shared control strategy with adaption to driver override behavior

A fail-safe architecture was developed for the vehicle behavior and motion planning module, incorporating shared control in response to driver intervention. This method estimates the driver's intention to collaborate on maneuver selection and distributes driving authority based on achievable minimal risk conditions. Using a receding horizon planner with composite planning horizons, the system ensures the driver can safely take over control. As shown in Figure 6, a critical scenario is created on a 3-lane straight road to test a fail-safe system's response to an intentional emergency event, involving lane changes, vehicle speeds, and a malfunction triggering driver intervention.

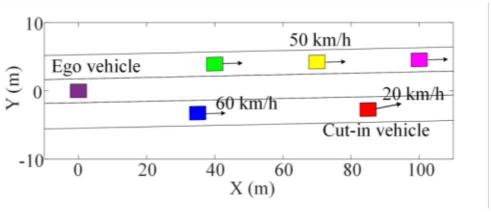


Figure 6. An illustration of the fail-safe test

When the system's chosen Maneuver Recommendation Module (MRM) aligns with the driver's intent, the driver typically regains control of the vehicle swiftly, with minimal distraction from the fail-safe system. The proposed system aims to intervene appropriately to correct the driver's erroneous behaviors when they execute a conflicting MRM. Figure 7 depicts the system's response to a panicked driver in a test scenario, wherein the system curtails unsafe acceleration but aids in completing a lane change correctly.

When the system's MRM choice diverges from the driver's intention, the system may reclaim control if the vehicle veers off its target under the driver's control. The heightened rate of control reclamation partly stems from this intention mismatch. Mismatched MRM selection typically arises from either the system misinterpreting the driver's intent or the driver's MRM failing to ensure a safe stop from the system's perspective. Regardless of the cause, the proposed system mitigates interference by resuming control when a safe stop is feasible. Figure 8 illustrates the vehicle's trajectory and state when the fail-safe system misinterprets the driver's intent to change lanes to the right. In such cases, the system overrides the driver's action and executes a fail-safe maneuver to halt the vehicle safely in the middle lane. Prioritizing a safe stop as the Maximum Restraint Control (MRC) strategy enhances safety during system-human conflicts. While prioritizing safety leads the system to halt the vehicle safely, it may diminish the driver's satisfaction with decision-making and erode trust in fail-safe systems.

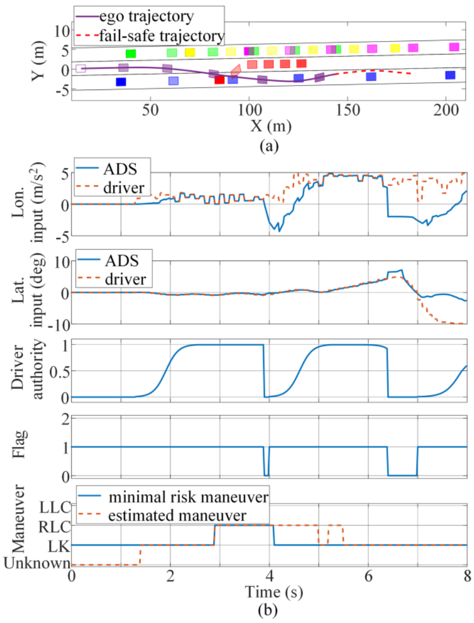


Figure 7. Performance when the system is consistent with a panic driver.

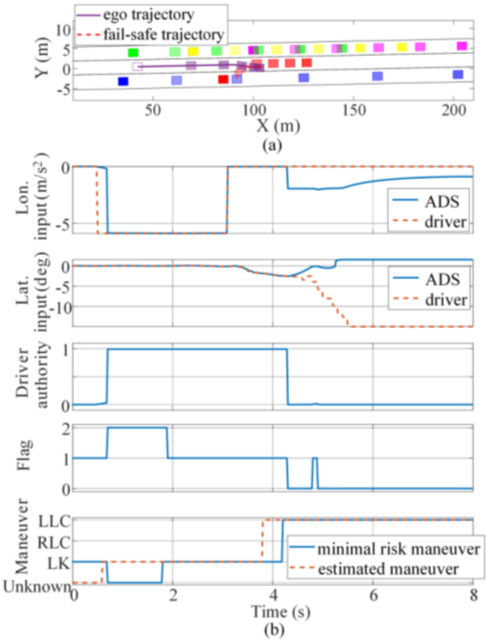


Figure 8. Performance when the system is inconsistent with a focused driver

(3) Developing a novel data-driven shared control paradigm based on mutual adaption for system with unknown dynamics

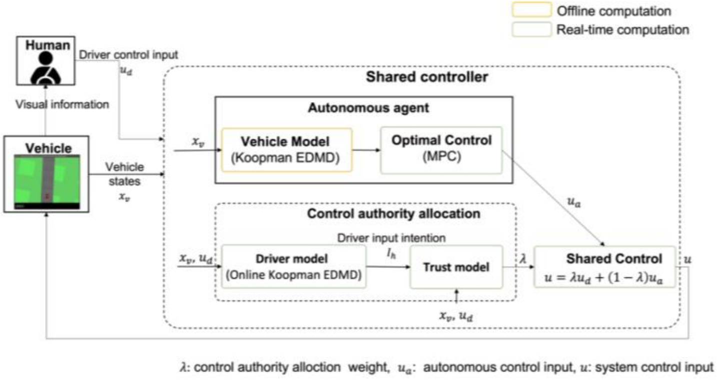


Figure 9. Schematic diagram of shared control with mutual adaption

As shown in Figure 9, a trust-based data-driven shared control strategy integrates driver and automation inputs through weighted summation, utilizing Koopman model predictive control for automation and a hybrid human-to-machine trust model for adaptive control allocation, demonstrated in interactive simulations where driver inputs inform an assistant controller for generating system control commands.In the experiment, Participants are asked to keep as close to the centerline of the route as possible under four control modes:

- User only control/ fully manual control (Usr)
- Trust based data-driven shared control (Tsc)
- Shared control with low level of automation when $u = 0.8u_d + 0.2u_a$ (Lsc)
- Highly automated shared control where $u = 0.2u_d + 0.8u_a$ (Hsc)

From the failure rate results in Table 1, it's evident that all shared control modes improve safety compared to user-only control, with highly automated shared control showing the best performance. Trust-based shared control exhibits fewer failures than lowly automated shared control but falls short of highly automated shared control. Table 2 highlights that trust-based data-driven shared control has the highest consistency ratio, slightly surpassing highly automated shared control and significantly outperforming lowly automated shared control. Additionally, the resistance ratio and contradiction ratio of Tsc are superior to Hsc, despite Tsc's average λ value of 0.256 being lower than Hsc's constant λ value of 0.3, suggesting that adaptive authority allocation enhances human-machine collaboration. Comparing contradiction ratios among the three shared control modes reveals Lsc<Tsc<Hsc, indicating that lowly automated shared control benefits from a consistent contradiction ratio, aligning with experimental findings where drivers' increased authority reduces system-induced frustration.

Table 1. Results of failure rate

Usc	Tsc	Hsc	Lsc
30.6%	9.72%	6.94 %	5.55%

Table 2. Results of collaborative behavior

Metrics	Tsc	Hsc	Lsc
Consistency ratio	0.472	0.444	0.261
Resistance ratio	0.131	0.150	0.388
Contradiction ratio	0.358	0.371	0.316

Figure 10 compares the cross-track error of four shared control modes, revealing that the average cross-track error follows the order Lsc<Hsc<Tsc. However, upon closer inspection, the distribution of Tsc appears the most concentrated, followed by Hsc, while Lsc exhibits the sparsest distribution. This suggests that trust-based shared control generally achieves better lane-keeping performance with minimal cross-track error, although an analysis of the raw dataset reveals that Tsc has significantly more instances of extremely large values compared to Hsc and Lsc. This phenomenon can be attributed to frequent system oscillations when large deviations from the desired trajectory occur under the Tsc mode.

Participants were asked to complete a questionnaire regarding their subjective workload. The results in Figure 11 indicate that all three shared control modes contribute to reducing driver workload. Specifically, Hsc demonstrates the most effective reduction in driver workload overall. However, Tsc does not perform well in reducing driver workload.

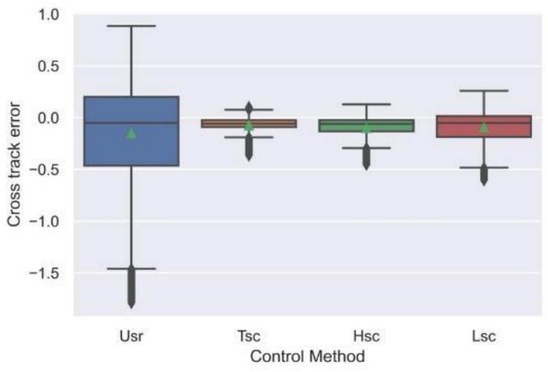


Figure 10. Comparison of lane keeping performance

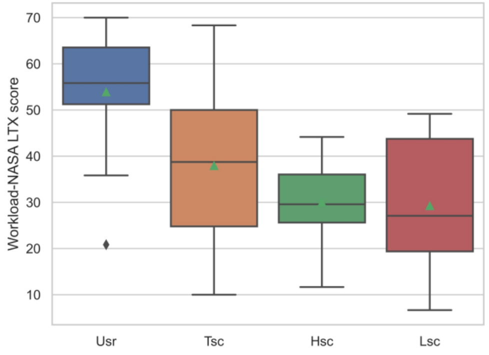


Figure 11. Comparison of NASA-TLX

５．主な発表論文等

〔雑誌論文〕　計9件（うち査読付論文　9件／うち国際共著　2件／うちオープンアクセス　4件）

１．著者名 Cheng Shuo、Yang Bo、Wang Zheng、Nakano Kimihiko	４．巻 23
２．論文標題 Spatio-Temporal Image Representation and Deep-Learning-Based Decision Framework for Automated Vehicles	５．発行年 2022年
３．雑誌名 IEEE Transactions on Intelligent Transportation Systems	６．最初と最後の頁 24866～24875
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TITS.2022.3195213	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

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２．論文標題 A Predictive Model of a Driver’s Target Trajectory Based on Estimated Driving Behaviors	５．発行年 2023年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.ifacol.2022.10.558	査読の有無 有
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掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/s21227691	査読の有無 有
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１．著者名 Nacpil Edric John Cruz、Wang Zheng、Nakano Kimihiko	４．巻 21
２．論文標題 Application of Physiological Sensors for Personalization in Semi-Autonomous Driving: A Review	５．発行年 2021年
３．雑誌名 IEEE Sensors Journal	６．最初と最後の頁 19662～19674
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〔学会発表〕　計5件（うち招待講演　0件／うち国際学会　3件）

１．発表者名 Wei Xue
２．発表標題 A Fail-safe System involving Shared Control Strategy for Driver Override
３．学会等名 Joint 9th IFAC Symposium on Mechatronic Systems and 16th International Conference on Motion and Vibration Control（国際学会）
４．発表年 2022年

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２．発表標題 Convolutional Neural Network-Based Intelligent Decision-Making for Automated Vehicles
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１．発表者名
Daihong Wan

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Trust-based Data-driven Shared Control for Lane-keeping

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第20回ITSシンポジウ

４．発表年
2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関