Autonomous Wheelchair Navigation

As automated driving system (ADS) technology is adopted in wheelchairs, clarity on the vehicle's imminent path becomes essential for both users and pedestrians. For users, understanding the imminent path helps mitigate anxiety and facilitates real-time adjustments. For pedestrians, this insight aids in predicting their next move when near the wheelchair.

1. Introduction

Wheelchairs are essential for people with mobility impairments, providing health and independence [1]. However, operating a wheelchair can be challenging for the elderly and those with upper limb injuries. Moreover, wheelchair users have a higher probability of upper limb injuries due to the use of their arms [2]. Additionally, the joystick controllers of electric wheelchairs are difficult for users with hand impairments [3]. If autonomous driving functionality is applied to electric wheelchairs, users could move to their desired destinations without the need to manually operate the wheelchair [2]. This would reduce their travel burden and enhance their independence in mobility.

The emergence of automated driving system (ADS) technology signifies a transformative epoch in intelligent autonomous mobility, especially in personal devices such as electric wheelchairs [2][4][5]. The adoption of autonomous driving technology enhances the convenience and independence of wheelchair users; however, these advancements introduce novel paradigms and conundrums in human–machine interface dynamics [6]. Contrary to conventional manual joystick mechanisms, autonomous wheelchair users often exhibit apprehension towards machine-dictated trajectories, which can appear as an opaque decision-making algorithm [7][8]. This transparency refers to "the degree of shared intent and shared awareness between a human and a machine [9]." Therefore, to achieve such transparency, the automated driving system needs to convey its capabilities, motion intentions, and anticipated actions to the user.

Notably, the terrains navigated by wheelchairs tend to be more complex than conventional vehicular roads [7][10]. The human visual system excels at interpreting these terrain nuances, often surpassing the discernment of standard machine sensors. Such intricacies, when amalgamated with instantaneous path determination, occasionally necessitate human interference, either through minor AI route adjustments or by re-assuming control. As shown in **Figure 1**, despite the commendable performance of ADS technology in many scenarios, there are still inherent challenges when confronting intricate road conditions and social interactions. This highlights the significant cognitive burden on users to comprehend the anticipated behaviors. It also reflects how transparent communication aids users in making decisions and intervening in the actions of the autonomous driving system. Moreover, it is essential for pedestrians to predict the autonomous wheelchair's anticipated actions, facilitating their own appropriate adjustments to prevent potential mishaps [11][12].
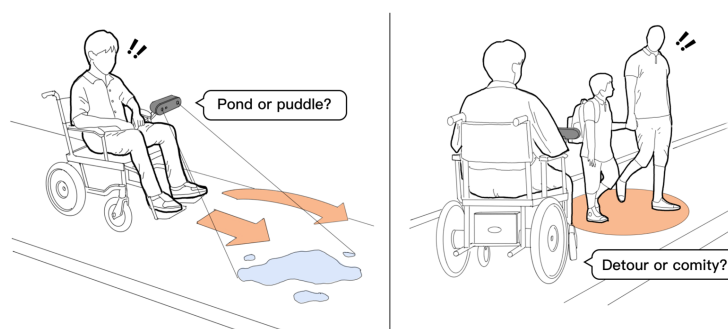

Figure 1. The limitations of autonomous driving sensors in discerning terrain nuances and social scenarios require user intervention for accurate distinction.

Thus, further study and exploration are required on how to effectively visualize the driving status and intentions of autonomous wheelchairs. This is crucial for enhancing the understanding of wheelchair users and other road users about the behaviors of autonomous wheelchairs and thus promoting transparent communication. Currently, there is a gap in the design and research specifically aimed at the visualization of driving status and intentions for autonomous wheelchairs. Additionally, there is a need to evaluate the impact of this human–machine interaction method on the attitudes and acceptance levels of both wheelchair users and other road users.

2. eHMI and Projection Interaction of Autonomous Vehicles

External human–machine interaction (eHMI) arises as a solution for the vehicle to transmit information to potentially dangerous agents in the vicinity, representing a newly developing direction of autonomous driving [13]. eHMI encompasses the interaction design between autonomous vehicles (AVs), pedestrians, and other road users, primarily involving the communication of the vehicle's status, intentions, and interaction modalities with pedestrians [6].

As ADS technology advances, the clarity and comprehensibility of such interactions become pivotal for road safety. Papakostopoulos et al. conducted an experiment and reported that eHMI has a positive effect on other drivers' ability to infer the AV motion intentions [14]. In addition, the congruence of eHMI with vehicle kinematics has been shown to be crucial. Rettenmaier et al. found that when eHMI signals matched vehicle movements, drivers experienced fewer crashes and passed more quickly than without eHMI [15]. Faas et al.'s study demonstrated that any eHMI contributes to a more positive feeling towards AVs compared to the baseline condition without eHMI [16]. These indicate that eHMI facilitates effective communication, reducing the uncertainty in intention estimation and thereby preventing accidents.

The design of eHMI could be multiform and multimodal. External interaction screens, matrix light, and projection interfaces are widely used in eHMI design due to their versatile interaction capabilities with diverse road users [17]. Among these, common visual communication modalities encompass emulation of human driver communication cues, textual interfaces, graphical interfaces, lighting interfaces, and projection interfaces [18][19][20][21]. Dou et al. evaluated the multimodal eHMI of AVs in virtual reality. Participants, as pedestrians, felt an increased sense of safety and showed a preference for the visual features of arrows [22], offering insights for future design. Dietrich et al. explored the use of projection-based methods in virtual environments to facilitate interactions between AVs and pedestrians [23]. Additionally, on-market vehicles have experimented with headlight projections to convey information. These highlight the implementation of projection as a visual form of eHMI, suggesting further potential for exploration in this area.

On lightweight vehicles such as wheelchairs and electric bicycles, eHMI in the form of on-ground projections is more reasonable. Utilizing on-ground projections, information can be directly exhibited on the roadway, offering explicit motion intentions or navigation paths. This approach of integrating interfaces with the environment through augmented reality offers communication that is intuitive and visibly clear, unaffected by the movement of vehicles [21][24]. Notably, augmented reality technology and multimodal interfaces are now considered effective means for ensuring smooth and comfortable interactions [25][26]. This provides insights for the exploration of more complex and engaging interfaces, especially through the method of on-ground projections.

eHMI has more value in social attributes and interaction design. According to the research of Clercq et al. and Colley et al [27][28], eHMI in the form of on-ground projections, particularly those conveying functions of autonomous driving mechanisms like parking and alerting pedestrians, are predominantly accepted by the majority of individuals. The experiment by Wang et al. [29] showed that this form of eHMI is safer, more helpful, and better at maintaining users' attention on the route.

Interestingly, for wheelchairs with on-ground projection-based eHMIs, this system serves not only as an external interaction tool but also plays a pivotal role in the user–wheelchair interaction due to the visibility of the projection in public spaces. Wheelchair users can observe the system's status through the projections and also interact with it, modifying its operational parameters, thus using it as a user interface for the wheelchairs. In the context of autonomous driving, ensuring the safety of autonomous wheelchairs on the road requires further exploration of their user and external interactions. There is also a need to develop specific and universally accepted UI system designs.

3. Shared-Control Wheelchair

Similar to the classification of autonomous driving, smart wheelchairs can be categorized into fully-autonomous and semi-autonomous control modes based on the degree of allocation of driving rights [30][31]. Different autonomous driving levels

have distinct control strategies, influencing user interaction and eHMI designs; this impacts the communication of wheelchair information to users, user control mechanisms, and the information shared with other road users.

In a fully-autonomous control mode, there are three possible scenarios for managing the allocation of driving rights for wheelchairs. Firstly, the driving right is completely handed over to the autonomous system, users simply indicate their destination, and the wheelchair navigates there without collisions [32]. Secondly, external collaborative control allows experienced individuals to remotely or directly control the wheelchair. Additionally, the driving rights of wheelchairs may also be controlled by a centralized system at the upper level, which uniformly allocates and manages the control of multiple wheelchairs [33][34]. This approach facilitates large-scale management, ideal for settings like hospitals and nursing homes that need centralized wheelchair oversight. Fully-autonomous wheelchairs have been found to overlook user capabilities and intentions. On the other hand, in semi-autonomous wheelchairs, users tend to favor maintaining control during operation and high-level decision-making processes [35].

The shared-control wheelchair employs a semi-autonomous control mode where the user and the autonomous system collaboratively determine the final motion of the wheelchair, aiming for a safer, more efficient, and comfortable driving experience [36][37]. The shared-control wheelchair will transfer part of the driving rights to the autonomous system. When the autonomous system is unable to determine or the user has a unique preference, the driving rights will be transferred back to the user for specific operations. Wang et al. discussed the human driver model and interaction strategy in vehicle sharing. This protects user experience when technology applications are limited [38]. Xi et al. [39] proposed a reinforcement learning-based control method that can adjust the control weights between users and wheelchairs to meet the requirements of fully utilizing user operational capabilities. High automation makes it suitable for wheelchair users who are unable to perform manual operations, such as those with high paraplegia and cognitive impairment.

Shared control encompasses two primary strategies. In the first, known as hierarchical shared control, users dictate high-level actions while the wheelchair autonomously handles collision avoidance [40]. The second strategy merges inputs from both the user and the motion planner, moving the wheelchair only when commands from both are present, thereby enhancing user control and collaboration [31][37][41][42]. Guided by these strategies to foster a more suitable human–machine collaboration for shared-control wheelchairs, the user retains higher-level decision-making while allowing the automated system to handle simple driving tasks. The wheelchair autonomously moves only when the user activates the autonomous mode. It automatically handles basic navigation by planning and selecting optimal routes based on user-specified destinations. Users can influence driving settings and motion planning with advanced directives in autonomous mode, such as adding temporary waypoints, yielding to pedestrians, or adjusting speed. Likewise, users have the authority to pause autonomous control for more detailed adjustments to the wheelchair's behaviors. These control methods ensure a harmonious balance between automation and user preferences in human–machine interaction, optimizing safety and user experience. And the driving information is communicated to both users and pedestrians through internal and external interfaces, ensuring clear and effective feedback for the success of the shared control systems [43][44].

4. Pedestrians' Concerns or Opinions about the Uncertainty of Autonomous Vehicles

The majority of previous research has focused on user acceptance of automated vehicles (AVs). Kaye et al. examined the receptiveness of pedestrians to AVs, partially filling the gap in research on pedestrian acceptance of AVs [45]. Pedestrian behavior is challenging to predict due to its dynamic nature, lack of training, and a tendency to disobey rules in certain situations [13]. Pedestrians may feel unsafe interacting with autonomous personal mobility vehicles (APMVs) when uncertain about their driving intentions. A lack of clarity regarding the APMV's intentions can lead to hesitation or even feelings of danger among pedestrians [46]. The understanding of driving intentions by pedestrians is by means of trust in human–machine interactions [47]. AVs are capable of reliably detecting pedestrians, but it is challenging for both AVs and pedestrians to predict each other's intentions.

Epke et al. examined the effects of using explicit hand gestures and receptive eHMI in the interaction between pedestrians and AVs. The eHMI was proved to facilitate participants in predicting the AV's behaviors [48]. In exploring interactions between pedestrians and autonomous wheelchairs, both Watanabe et al. and Moondeep et al. identified that explicitly conveying the wheelchair's movement intentions, through methods such as ground-projected light paths or red projected arrows, notably enhanced the smoothness of interactions and augmented pedestrians cooperation [49][50]. This underscores the significance of transparently communicating driving intentions in alleviating pedestrians concerns regarding the uncertainty of autonomous vehicles. However, interactions and scenarios between autonomous wheelchairs and pedestrians, such as yielding behaviors of the wheelchair, have not been extensively studied. Moreover, the

systematic exploration of eHMI used in autonomous wheelchair is needed, along with research into pedestrian acceptance based on these systems.

5. The Sociology of Wheelchair eHMI and the Image of Wheelchair Users

With the gradual development and popularization of the shared-control wheelchair, ADS technology will face more challenges and new design opportunities. In this context, eHMI holds potential to enhance public trust in such technology [13]. eHMI not only offers a clear interactive interface, but also helps pedestrians and other road users understand the intentions and behaviors of vehicles [51]. This can reduce anxiety and concerns about the transfer of control to machines or others within the context of shared control between drivers and the autonomous system. Due to the feature of real-time interactivity, eHMI could become the interface to communicate with society, enhance society trust and help vehicle users convey their emotions and intentions.

Wheelchairs, as vital empowering tools, also represent a continual visible sign of disability, attracting unwanted attention and potentially leading to social stigma [52]. Wheelchair users, sensitive to this, often prefer visual over auditory communication in their daily interactions to avoid such issues [53]. As a vulnerable group, wheelchair users require enhanced driving support and comfortable, engaging external interactions for a valued and self-acknowledged image in society. The experience of users with on-ground projection interfaces is worth exploring to investigate how eHMI can enhance societal understanding and trust in autonomous wheelchairs, fostering more empathetic and friendly connections between users and society.

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