Mixed Reality Agent-Based Framework for Pedestrian-Cyclist Interaction*

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Abstract

Participating in urban traffic is inherently risky for humans. Therefore, in psychology, behavioural studies have been using Virtual Reality (VR) to simulate and experiment with human behaviour. Safety critical interactions (e.g. conflict, collision or near collision) can be captured from the motion trajectories. However, the motion data in virtual settings is influenced by the modelling software used to create the virtual world, which might fail to capture one-to-one interactions accurately (such as interactions between pedestrians and cyclists in mixed traffic). Our system paper proposes a Pedestrian-in-the-Loop (PIL) Mixed Reality (MR) framework, where mobile virtual cyclist avatars co-exist with humans in a real-world outdoor space. Such a setting can be used to study a pedestrian subject, both viewing and interacting with moving holograms of cyclists in real traffic. The novelty of our approach is modelling virtual avatars as cognitive agents. To achieve this, we integrate agent-based models so that the virtual avatar can sense the environment and interact with the real user participating in the experiments. We demonstrate that this approach could contribute to effectively studying of pedestrian interactions. We also perform an evaluation to quantify the amount of trajectory error for our outdoor framework. For this, we compare the position data of a subject during an experiment to a proven benchmark for indoor motion capture. Additionally, an application of using the framework to demonstrate pedestrian dominance is presented.

Index Terms: Mixed Reality—Interaction modelling—shared spaces—safety; Simulations—Behaviour—Pedestrian in Loop

1 Introduction

Active modes of transportation like walking and cycling have recently received much attention [2] and are also promoted for being sustainable, healthy and environmentally friendly. Urban environments such as *shared spaces* [13], where heterogeneous modes (e.g., pedestrians, cyclists, and vehicles) share common road space, also increasingly accommodate walkers and cyclists, reducing vehicular dominance. Road users negotiate the right of way in shared spaces via social interactions, such as hand gestures [1, 8].

When pedestrians share the same space with cyclists, safety becomes a serious issue. In [5], Batista et al. identified that 28% of interactions between pedestrians and cyclists resulted in potential conflicts in a shared environment. This is higher than the pedestrian-motor and cyclist-motor figures, 22% and 25% respectively.

If safety-critical interactions such as conflicts, collisions and near collisions can be simulated with more realistic trajectories, the underlying motion data can be used in research studies to understand the context leading to dangerous behaviours. For example, a stable

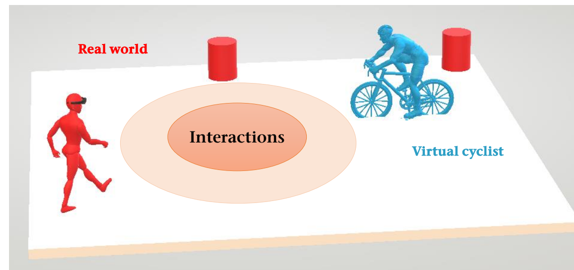

Figure 1: A real pedestrian walking and interacting with a virtual cyclist in a mixed reality setting with other virtual content

walking motion path can indicate a person confident of the local rules, while erratic walking patterns might better indicate him to be a tourist who was unaware of priority rules [29]. If such prior information is available, he could be given "guidance" [20]. In [21], Kamalasanan et al. propose a wearable AR interface that can signal pedestrians to stop if a collision is detected. The system would give priority to the person with higher speed. In [29], a dominance score is identified based on motion information for pedestrian and autonomous vehicle interaction. This is used to decide who would have the right of way in a crossing scenario.

With the advancement of Mixed Reality (MR), mixing real-world elements with spatially aligned holograms has become a reality; this creates new opportunities for pedestrian-in-the-loop (PIL) interaction simulation. Virtual holograms of 3D traffic agents (e.g. cyclists) can be added to the scene to study complex interactions in shared spaces. Such mixed reality PIL simulations would require frameworks that are capable of reproducing realistic traffic trajectories of both real and virtual content and also scalable (i.e., to support many moving scene objects) and .

Motion trajectories captured in PIL experiments would depend on the positioning accuracy of the data capture apparatus capturing the subject under observation. MR headsets (e.g., Hololens 2) with a positioning accuracy of under $2cm$ [35] could be an ideal fit. Also, while viewing virtual holograms is important, realistic speed and motion manoeuvre for virtual content are paramount if interactions have to be recorded. This would also require integrating shared space simulation frameworks that are proven for mixed traffic with PIL simulations.

Agent-based modeling has been widely used for microscopic traffic simulations [14,22]. The notion behind agent-based modelling is that agents can act and interact autonomously with other agents as well as the environment. Recently, agent-based modelling has been considered in shared spaces, where road user interaction has been investigated, and modelled [19].

To the best of our knowledge, there is no simulation models for mixed-traffic environments that perform interactions among real and virtual road users. The contribution of this work is to realize an MR framework for behavioural simulation that involves connecting stable holographic rendering with an accurate simulation model of shared space traffic agents. A shared space mixed reality system, which would accurately model traffic agent behaviour, could prove

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beneficial as an apparatus for psychological studies for conducting experiments in *live settings*.

The rest of the paper is structured as follows: In section 2, background and previous work related to VR/MR in understanding human behaviour and integrating agent-based modelling with VR/MR are reviewed. We present our novel framework and its architecture in section 3. Section 4 describes our modelling approach and the realization of the framework. Additionally, this section shows the evaluation results. Our experiments' in-depth explanation and discussion are presented in section 5. Finally, the conclusion has been drawn in section 6.

2 Related Works

2.1 Mixed Reality and Interactions

The ability to move continuously between virtuality and the real world is one of the main characteristics of Mixed Reality [25]. Artificial experimental settings in MR create more realistic experiences over VR with virtual content embedded in the real-world setting. These have enabled realistic but controlled interaction scenarios. To understand the potential of using mixed reality for interactions [28] focused on proxemics [12]-to understand how humans manipulated distances in the presence of other virtual humans. In this work, the social distances in MR with virtual characters were comparable to those found for human-human interpersonal distances. In [10], an MR framework was proposed as a testbed to study social interactions while engaging with a digital MR character. In the work, the authors used a game theoretical approach for the virtual content, which was used to identify behavioural patterns in subjects in controlled settings. This was further used to explore psychopathological traits or other behavioural aspects of the subjects under study. However, to the authors' knowledge, none of the work has focused on interaction modelling using motion data from a traffic perspective.

2.2 Use of VR/MR and Understanding Human Behaviour

While pedestrian-cyclist interaction simulations have not been attempted with mixed simulations so far, mixed reality simulators for cyclists have been used to improve safety. An MR cyclist simulator presented in [34] focused on how children could benefit from "virtual" traffic education. The work proposed a bicycle simulator that can be used in a CAVE, with a VR headset, or as a standalone PC simulation to explore the different aspects of research on human factors and cycling. Iryo-Asano et al. [18] developed a VR environment to analyse pedestrians' cognitive and behavioural characteristics towards others. In that work, the behaviour of surrounding pedestrians was also realised using an interactive model, in which the forces represent the acceleration vectors of pedestrians in the environment. In this and several other works, the Social force model (SFM) [15], and other variants of the same have been used to model the behaviour of pedestrians.

Pedestrian one-to-one interaction experiments focused on collision avoidance by coordinating the walking path or speed for collision avoidance [16]. The motion of a pedestrian was also noted to be influenced by complex geometries in the environment. Turning movements were observed by Dias et al. [11] in a series of walking experiments in angled corridors. To better understand human collision avoidance behaviour in curvilinear trajectories, virtual humans were used in Virtual Reality (VR) settings [23]. Experimentally controlling curvilinear trajectories with repeatable normal acceleration is a difficult task; hence virtual human avatars in the experiment offered a novel simulating approach. A collision avoidance situation between a real participant and a virtual character was studied in [27], wherein the authors observed that participants accurately anticipate the risk of future collisions. Even so, there were significant delay issues due to the VR setting. Our idea is similar to the stated work where a virtual walker is used to study the motion dynamics of pedestrian walkers. Moreover, we experiment with Mixed Reality

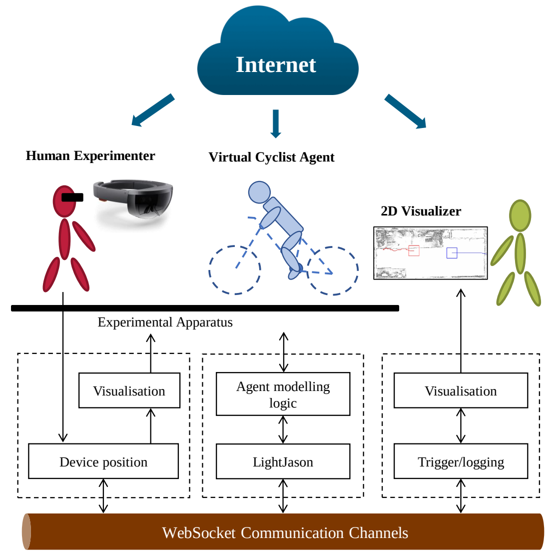


Figure 2: Different components of the real and virtual world interconnected using web sockets

for pedestrian one-to-one interaction with a cyclist and see if some of the shortcomings of a VR setting can be addressed.

2.3 Integrating agent based models with VR/MR

Agent-based crowd models have been used in virtual environments to fine-tune simulations better, while, on the other hand, VR environments have been used to identify simulation parameters for agent-based crowd simulation [31]. In order to create more realistic crowd models, CAVE experiments were used to collect data with human-in-the-loop testing. Based on the times a path is taken by the test subjects in VR, a weight value was calculated to quantise the importance given to a specific parameter in agent models.

Exploiting the agent-based models for augmented reality applications has been presented in the platform Augmented Worlds [9]. In this work, the authors showed the concept of bi-directional augmentation in two use cases; an augmented museum and an augmented harbour. A recent work that significantly overlaps with ours has been proposed in [26], which integrates an agent-based pedestrian model from a software called *Anylogic* with mixed reality to achieve pedestrian simulation for evacuation scenarios. However, none of the above-stated works emphasised scalability as an issue. As we focus on traffic, we look at the available agent-based frameworks and choose LightJason [4].

In summary, the contribution of this work can be summarised as follows:

- We present a new approach for using mixed reality to collect motion data of a pedestrian encounters a virtual cyclist.
- We realise a workflow with essential components for such a framework and emphasize how they interact in a real environment (real-world settings).
- We highlight the benefit of our framework for future mixed traffic simulation, enabling augmented pedestrian-in-the-loop.

3 The Mixed Reality Agent-based Framework

This work presents our novel mixed reality agent-based framework, where real participants coexists with virtual agents, controlled by a multiagent system. The framework depicted in Figure 2 follows the

Figure 3: The workflow for the proposed framework that includes modelling the test environment, simulation and the experiment data collection

client-server architecture; the server runs an agent-based simulation model, the first client is the Hololens headset of the human experimenter, and the second client is the 2D visualiser. As our objective is to focus on pedestrian-to-cyclist interaction, our framework should support the presence of the virtual content, the realistic motion simulation of a 3D virtual cyclist and the recording of motion data of the pedestrian to sub-meter accuracy. While the former two were required to achieve realistic interaction, the latter was equally important as we targeted to analyse the motion trajectories of pedestrians who would be involved in the experiments.

In our framework ,a person walking and wearing the Hololens headset (Human experimenter), can see a virtual 3D cyclist avatar in his field of view. The position information from the Hololens device that results from the computer vision algorithms (like SLAM [33]) is used to localise the person in the mixed reality environment. This 3D position information is synchronised in real-time using WebSockets via the internet.

The agent-based simulation model performs microscopic simulation between the real pedestrian, based on the experimenter's position, and next collision-free position for the virtual cyclist agent in the environment. The simulation responses move the cyclist avatars in the mixed reality world. This mixed interaction between real and virtual worlds can be viewed in a 2D visualiser, where the real and virtual agents' motion trajectories, and all the interactions happening, can be recorded for offline analysis and further replay.

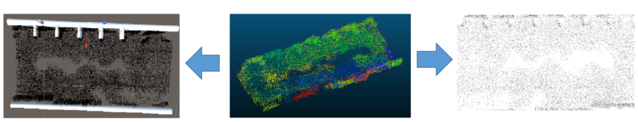


Figure 4: The acquired point cloud is processed to help extract the 3D model (for the HoloLens) and the 2D map (for the visualiser) of the test environment

Existing works on interaction simulations have experimented with multiple virtual reality setups that included either purely virtual, game controller, screen or CAVE-based [7]. However, our design choice of using the HMD-based mixed reality setting was to improve the "realism" of the pedestrian involved in the real-world experiment. Also, we avoided including additional hardware on the HMD or trackers on the foot [24], as we wanted the subject in the experiment to feel as natural as possible. As for the positioning, we choose the Hololens 2, which has a proven accuracy of $\pm 2cm$ in indoor spaces [17].

4 The Framework Realization

Figure 3 illustrates the workflow of the framework that includes: Modelling the Mixed-Real Environment, Mixed-Reality Simulation and Data Collection.

4.1 Modelling the Mixed-Real Environment

In this step, a simple 2D and virtual 3D representation of the environment is created that would be used for the real-world representation and virtual world alignment, respectively (Figure 4). As our intended framework is focused on shared spaces with reduced or no infrastructure, we have proposed a more straightforward approach to modelling the 3D environment.

3D Modelling: The Hololens 2 research mode [33] allows the access of raw sensor streams as 3D point clouds. In the modelling step, we capture the 3D point cloud of the scene by extending the StreamRecorder [1] with ROS[2]. The captured point cloud was preprocessed, downsampled and cleaned to obtain a point cloud of the test environment. The point cloud was imported to Unity to manually create a virtual representation of the enclosing boundaries using primitive Game objects[3] like Cylinders.

2D Modelling: The raw point cloud in the previous image is further converted to a Birds Eye View (BEV) image to visualise the interactions from a third-person perspective via the viewer Utility; the 2D visualiser. The processed map of the test space is quantised and transformed with each 50-pixel grid representing a world dimension of 1m.

For the MR experience, the 3D virtual world designed in Unity is aligned to the real-world using QR code markers placed in the environment. In this step, the Unity coordinate system is aligned and locked to the real-world coordinate system using World Locking Tools[4].

4.2 Mixed Reality Simulation

In our work, we focus on capturing motion dynamics in the event of a near collision [32]. To perform microscopic simulation between the real and the virtual agents, we chose *LightJason* [4] for two main reasons: (1) it has been demonstrated for mixed traffic simulations [19], and (2) easy to customize [3]. With LightJason, we implemented a simulator and deployed it to a server, in which the environment has been designed as a fine-grained 2D grid with a cell size of $0.1m$. The agent description of the cyclist is written in AgentSpeak(L++) language. All interactions that happened inside the simulator are replicated in the 3D view in the HoloLens.

In our prototype, we design fixed paths for virtual cyclist navigation while modelling free movement for the pedestrian. The virtual cyclist starts at the origin position and ends at final the destination (OD), passing through intermediate waypoints. The waypoints are passed as prior information to the framework to plan the cyclist's motion, and once the above prerequisite step is complete, the simulation can be started.

The human experimenter (see Fig. 2) connects and sends his position in real-time; the virtual agent will have the ability to detect the real agent and therefore avoid the collision. The multiagent interactions are enabled using WebWockets for real-time state updates. Stomp messages are used to maintain the publish-subscribe massaging mechanism between the different components via a wireless medium connecting the Unity environment on Hololens and the simulator on the server.

4.3 Data Collection

The *2D visualiser* is developed as a viewer so that all the interactions can be seen from a BEV perspective. The 2D visualiser receives real-time updates from both the Hololens and the multiagent system using WebSockets. The tool includes a GUI to view the interaction from a

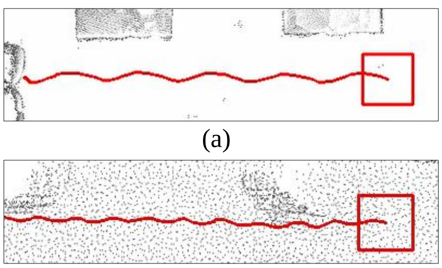
[1] https://github.com/microsoft/HoloLens2ForCV/
[2] https://www.ros.org/
[3] https://docs.unity3d.com/Manual/GameObjects.html
[4] https://microsoft.github.io/MixedReality-WorldLockingTools-Unity

2D perspective using the 2D map created in the modelling step. The GUI also supports the trigger of simulations allowing experiments to be completed without the involvement of the interacting Hololens participants. Furthermore, it allows recording such interaction data for each experiment iteration. These data can be used in future for understanding pedestrians dynamics involved in interactions with cyclists in mixed traffic areas.

4.4 Experimental Evaluation

As most of the PIL experiments happen indoors with the subject tracked via installed motion cameras etc. We use the proven/published positioning accuracy of the Hololens device for indoors [35] as baseline and benchmark the motion trajectory accuracy for our outdoor framework.

To have a baseline for comparison and evaluate the positioning accuracy in our framework, we designed two experiments: indoor and outdoor. We constructed a straight line matching the curb line inside the mixed reality environment. A volunteer was asked to walk along the line to benchmark the device's accuracy in recording a linear path. Figure 5 shows HoloLens trajectories of the experimenter outdoor and indoor[5].



(a)

(b)

Figure 5: Screenshots from the 2D Visualizer for (a) indoor trajectories, and (b) outdoor trajectories

Figure 6 shows the violin plot for the localisation error comparing indoor and outdoor spaces. Due to the swaying motion of the pedestrian, which happens while moving his/her legs, we can see from the plot that the device recorded a maximum error of $\sim 5cm$. However, the error was as high as $10cm$ for outdoor setting. The mean error in positioning for the indoor setting was $\sim 2.4cm$ and for the outdoor case was $\sim 4cm$. Accurate error benchmarking experiments should be completed in future, considering weather conditions to evaluate the simulation trajectories better.

5 Case Study: Pedestrian Dominance

The motion dynamics of a pedestrian reacting to a heads-on interaction with a cyclist can help to identify underlying traits (e.g. mood, emotion, level of attentiveness). For example, an upset person would have a motion trajectory with erratic patterns, which would differ from someone who is preoccupied with his phone and not observing an approaching obstacle. There is great potential in understanding emotions from underlying trajectory data [30].

[6] et al. classified traits as six weighted behaviour classes: aggressive, assertive, shy, active, tense, and impulsive. They used motion trajectories for local behaviour modelling based on these traits to improve crowd simulations. For the scope of our work, we demonstrate that the dominance of human motion can be realised. We would call a pedestrian dominant if he decides not to give the right of way in interaction and non-dominant or submissive if otherwise.

[5]Based on the environment, we used different scales for indoor and outdoor, which affects the swaying range

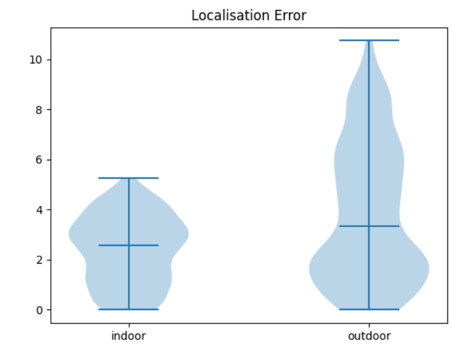


Figure 6: Error in positioning for a pedestrian following a straight line path

For the demonstration, a volunteer calibrated the environment by aligning the virtual landmarks with real-world elements using QRcode scanning. Two experiments that have been conducted will be described, and the results will be discussed in the following two sections respectively.

5.1 Experiments

Experiment 1: Dominant Behaviour In this experiment, the pedestrian walked, crossing his path with the virtual cyclist. He was instructed not to react to the cyclist in the event of a collision. This situation would mimic a distracted pedestrian focusing on his smartphone or an aggressive pedestrian in traffic. Figure 7 represents the planned trajectory and the interaction modelled via agent-based modelling.

Figure 7: The human experimenter walking briskly towards the cyclist, enforcing the right of way

Experiment 2: Submissive Behaviour In this iteration, the experiment was designed to obtain a realistic pedestrian trajectory when he decides to give the right of way to a cyclist to avoid an encounter. For this, the pedestrian was asked to walk naturally as an active participant altering his motion trajectory in the sight of the cyclist (see Fig. 8).

Figure 8: The human experimenter walking cautiously giving the right of way to the cyclist

5.2 Results and Discussion

For ideal lighting conditions, the HoloLens shows sufficient stability in terms of performance and redenering of 3D avatars. With the aligned environment,the virtual cyclist is seen moving in his path at his preferred speed. For simplicity, we keep the speed constant at $2m/s$. Throughout the experiments, an average rendering performance of 57-60 fps was observed.

For *Experiment 1*, as the pedestrian was instructed to keep looking at his smartphone, he started noticing the cyclist when it came close. Although he kept moving, crossing the 3D cyclist path, the cyclist reacted; it stopped, changed its direction and successfully manoeuvred the real pedestrian. Figure 9 shows the change in the cyclist's trajectory while the real pedestrian was moving straight into his destination. That means the virtual cyclist could percept the environment and see the real pedestrian, which tried to avoid colliding with him.

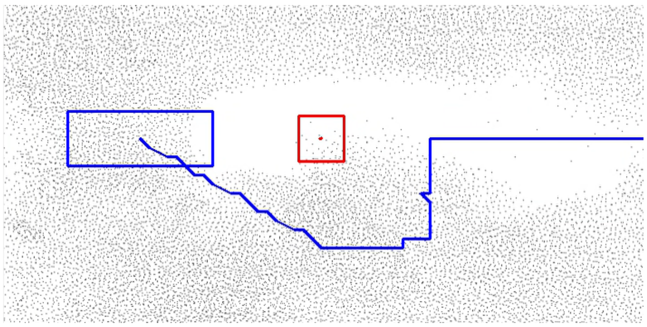


Figure 9: The virtual cyclist (blue) forced to take a detour as a dominant Human experimenter (red) blocks his path

On the other hand, in *Experiment 2*, the situation was different.The pedestrian was instructed to be aware of the environment and look into his walking path and surroundings. As in this scenario, the virtual cyclist appeared to be moving toward its destination, and the real pedestrian could successfully identify his moving direction. As the virtual cyclist was coming close to the pedestrian, the pedestrian avoided him and took a detour. Figure 10 shows the reaction of the real pedestrian and the change in his trajectories toward the virtual cyclist.

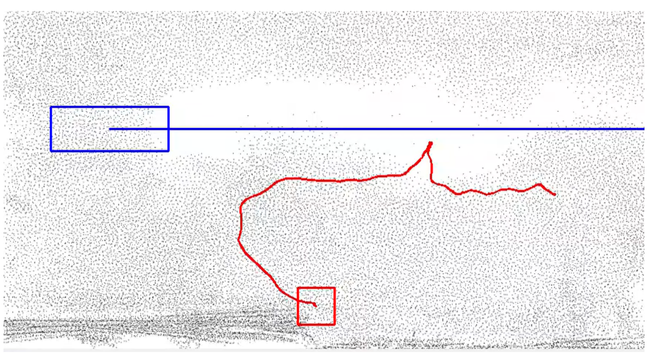


Figure 10: The virtual cyclist (blue) uninfluenced by the existence /path of the Human experimenter (red)

6 Conclusion and Outlook

This paper presented a novel mixed reality agent-based framework that enables pedestrian-in-the-loop interaction simulation with a virtual cyclist. The real pedestrian can identify the 3D virtual cyclist in the real environment, while the virtual cyclist has the ability to percept the presence of the pedestrian in reality. We complete evaluations for position error in motion trajectories of the human subject involved in outdoor experiments and also demonstrate interactions can be simulated with mixed reality.

However, while we can show that the framework enabled the interactions of the real pedestrian, we observed technical instability issues in multiple experiments. A large proportion of the technical issues was in having stable, consistent rendering of virtual content. We observed that this was also due to the weather condition (wind gusts or poor/high lighting). Our initial observations noted that the virtual 3D avatar moved to the next free cell as expected when being blocked during the interaction. Nevertheless, in multiple runs, the virtual agent (cyclist) however moved into the real pedestrian, missing to have seen the presence of the pedestrian . However, we have not focused on a benchmarked cyclist simulation model for the current implementation. This will be a subject for future work.

With this work, we have realised a base system supported by a prototype for interaction simulation. However, thorough experimental (empirical) analysis is to follow, looking into to what extent humans find the system realistic (immersive) and if they would prefer the system (over, e.g. traditional 2D/3D simulation). Also as our focus is on trajectories of both real and also virtual, we plan to propose a more realistic cyclist model and consider different modalities, such as mopeds and autonomous vehicles, as a part of our future works.

Acknowledgments

This research is funded by the German Research Foundation (DFG) through the Research Training Group SocialCars (GRK 1931).

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