Simulating Disturbances in Tactile Internet to Study Desynchronization

Neil Van Acoleyen
Supervisor(s): Kees Kroep, Dr. RangaRao Venkatesha Prasad
EEMCS, Delft University of Technology, The Netherlands

23 June 2022

A Dissertation Submitted to EEMCS faculty Delft University of Technology,
In Partial Fulfilment of the Requirements
For the Bachelor of Computer Science and Engineering

Abstract

As technology evolves, transmission speeds become faster. Tactile Internet requires ultra-low-latency (ULL) communications to further immerse humans in a remote environment by transmitting movement and force feedback, allowing them to interact with that environment in real-time. However, no transmission speed can be fast enough to support the "1 ms challenge" over long distances due to light speed limitations. A system with over 1ms of delay will feel unnatural to the user and cause "cyber-sickness". A novelty solution solves this by simulating the remote environment locally using point clouds. The system is then able to compute the force feedback immediately. This paper focuses on the desynchronization between simulation and reality that can build up due to disturbances. A framework for testing and observing desync caused by controlled disturbances is built for this purpose. The framework can also be used to test possible solutions to this issue. 1-dimensional simulations show that divergence happens slowly for friction and mass mismatches, providing a time frame during which it can be corrected. 2-dimensional simulations presented non-deterministic results, limiting the observations.

1 Introduction

Tactile Internet (TI) enables the transmission of physical movement and haptic feedback over the internet. Pairing this with audiovisual information, humans will be able to remotely operate systems and interact with their environment as if they were themselves present in that environment [1], [2]. The use cases for this technology are countless, for example, a surgeon could perform surgery from his home, disaster management could happen remotely and professional ping pong players could train against opponents located in different countries.

Before it all becomes possible, the main problem that remains to be solved is the "1 ms challenge". Over 1 ms delay is noticeable to the user [3] and leads to imprecise manipulations in addition to degradation of the system's stability [4]. Light limitations alone make this requirement unachievable over long distances using a standard feedback loop. With communication traveling at the speed of light, a round trip to the other side of the earth would cost approximately 133 ms. Without considering any disturbances, this already far exceeds the delay requirement.

A solution is proposed for this problem. Instead of receiving the haptic feedback directly from the other side, each side possesses a local simulation of the opposing environment, recreating what the effect would be [5]. The master domain is the term attributed to the side where the user is situated. The controlled domain represents the side containing the environment which the user interacts with. A schematic is shown in Figure 1. This solution relies on accurately being able to capture an environment to create a model of it. Point clouds

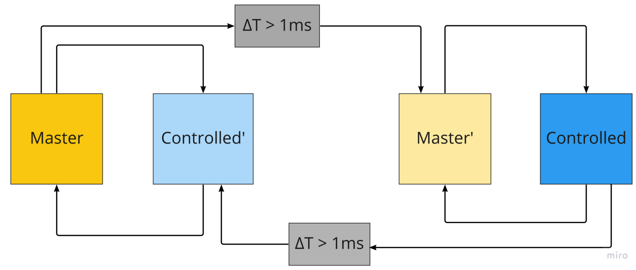


Figure 1: Box diagram visualizing how each domain interacts with their local simulation of the opposite domain to obtain direct feedback

are used to achieve this [6]. These are RGB values augmented with a depth value. Creating a model for both domains allows for direct computation of force feedback, meaning that delay requirements can be relaxed. However, this solution brings other challenges to tackle. One such challenge is the desync problem.

Eventually, when simulating an environment without correction, disturbances and incorrect measurements/predictions will stack up and cause the virtual environment to no longer be the same as the physical environment. In other words, there is a desynchronization between model and reality. For example, this could mean that the same object is at two different locations in the domain and its model, leading to problems when interacting with that object. This desynchronization is destructive to the system and needs correction. However, the nature of the effects caused by it is still unclear and remains to be studied. This paper tackles the question: "How can we gain insight into desynchronization between master and controlled domain in TI?". The question can be divided into two parts:

1. Adding controlled disturbances to the TI system and causing desynchronization.
2. Observing the effects and how long it takes to break the system.

The contributions of this paper are the following:

- Identification of disturbances that cause desync and a study of their effects.
- Implementation of a simulator adding controlled disturbances to a TI application. The effects caused are reproducible. The simulator can be used to test out correction algorithms to patch up desync.

The structure of this paper goes as follows. First, some related works in the field of TI are presented in section 2. Then, the design choices and experimental setup are detailed in section 3 and section 4, respectively. The results can be found in section 5. Afterward, the reproducibility of the work is discussed in section 6, followed by some recommendations for future work in section 7. Finally, the conclusions are stated in section 8.

2 Related Works

Tactile internet is still a long way from reality as it presents multiple challenges [7]. The most critical one being the 1 ms delay requirement [8]. Network requirements are a big part of TI. Internet of Things (IoT) and 5G share a lot of these network requirements [9]. For example, all three of them require ultra-low-latency, ultra-high reliability and security. For this reason, 5G will probably act as the foundation of TI [8], [10]–[14]. As for first/last mile communication, the best candidate is WiFi-7 [1]. Haptic devices are also a fundamental part of TI. These are the devices responsible for providing the tactile information to the user. However, current technology is not advanced enough for TI and new devices are needed that can provide both tactile and kinesthetic feedback [7], [8]. D. Van Den Berg et al. offer a summary of the challenges in the field of TI.

A lot of work is needed for realizing tactile internet. However, the applications are numerous and groundbreaking [15]. TI has the potential to revolutionize many fields, including but not limited to healthcare and education [15]. The possibilities make it worth the effort.

Gokhale V et al. present a testbed to provide a common ground for benchmarking TI and also provide the TI Demo used in this paper.

3 Methodology

This section explains the design choices made to answer the research question. Gaining insight into desynchronization between the master and controlled domains requires being able to simulate disturbances in a controlled environment. The simulator designed for this research question builds on top of an existing TI demo [2]. It is developed in Unity[1] using modified bullet physics[2]. The demo has the advantage of using the same mechanics as the TI system and avoids building everything from the ground up, which is not the focus of this paper. The following steps were taken to tackle the problem. First, the complexity of the space was reduced. Then, TI applications were designed utilizing the novelty solution to the "1 ms challenge" described in section 1. Afterward, controlled disturbances were simulated in the TI applications. Finally, tests were implemented to observe the effects of disturbances on desynchronization. The following subsections discuss in detail the approach for every step.

3.1 Reducing the Complexity

The motivation behind studying desynchronization is to collect enough data to find a correction method afterward. Finding a solution directly in a 3-dimensional space is expected to be highly difficult. Reducing the complexity of the environment would allow testing simple cases first. For this reason, the TI applications recreated were 1-dimensional and 2-dimensional. Since the demo's physics engine is 3D, restricting movement along one axis simulates 2D and restricting movement along two axes simulates 1D.

3.2 Recreating a TI Application

To recreate a TI system, two copies of the same environment were added into a Unity scene. One copy of this environment represents the master domain. The other copy represents the controlled domain. Regardless of the dimensionality of the space, the application implemented consisted of a ball pushing a block. In this simple environment, it is easy to observe desynchronization when the copies are displayed side by side or stacked on top of each other. The causes for desynchronization are also easily identifiable due to the lack of complexity.

3.3 Adding Disturbances

The next step in the process was to implement the disturbances. These were divided into two different categories. The first category grouped the network-related disturbances. The second category corresponded to physical property mismatches that could occur when capturing an environment with point clouds.

In the category of network-related disturbances, we can identify two main problems: network delay and packet reliability. The network delay was simulated by having the controlled domain start its ball path at a later timestamp. Delay alone should not cause desynchronization as it does not alter any data. This observation factors in that there is still no feedback applied, meaning that the location of the controlled domain's cube does not influence the master domain's cube. For this reason, latency was not included in the tests to allow for direct comparisons between the two domains. No network component was yet implemented in the TI Demo. For this reason, the controlled domain followed the ball path instructions directly on its own physics thread. In an attempt to simulate packet reliability, ball movement instructions were dropped at the controlled domain according to a certain probability. However, the refresh rate of the physics engine, which included the ball movement instructions, was too fast for this, essentially negating the dropped instruction. With a refresh rate of 1 ms, this simulation for packet reliability was unrealistic. Given the short timeframe for this work, no other solutions were tested out.

The category of physical property mismatches can be summarized by any difference in the physics engine data of two copies of the same object. These are vast and impact the behavior of the system in multiple ways. This work only focuses on a specific set of data: the mass and friction of an object. In the context where a ball is pushing a cube around, these physical features seem to be the most relevant. In addition, they are also information that is difficult to extract from only point clouds. For example, how would the system know for certain if an object is hollow or filled on the inside based on only vision? Humans would also have difficulty answering this question without lifting the object. Size and shape mismatches were also considered but were deemed less likely to happen given the nature of point clouds.

3.4 Reproducible Tests

The last step of the process was to set up some tests and begin observing some results. A test is a preprogrammed path that the ball follows. Initially, this was performed by passing a collection of instructions to the physics engine through Unity. However, replaying the same path with the same set of disturbances would yield different results. To mitigate this non-deterministic behavior the path was implemented directly into

[1]https://unity.com/

[2]https://github.com/bulletphysics/bullet3

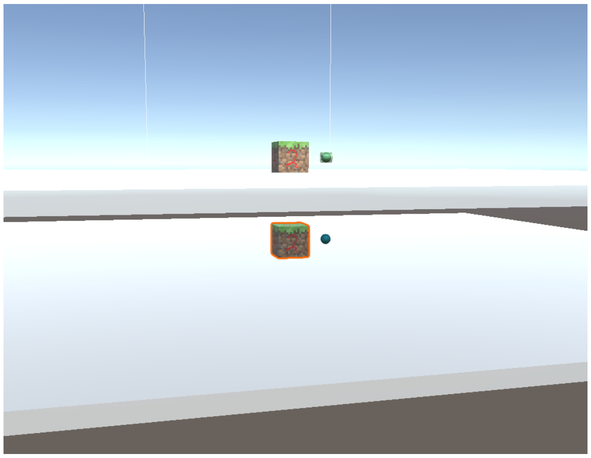


Figure 2: The experimental setup. The top cube and ball represent the master domain. The bottom cube and ball represent the controlled domain

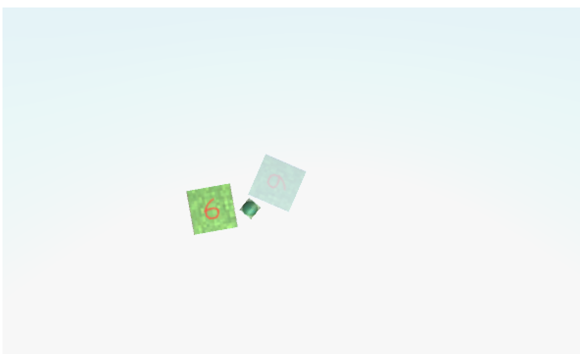


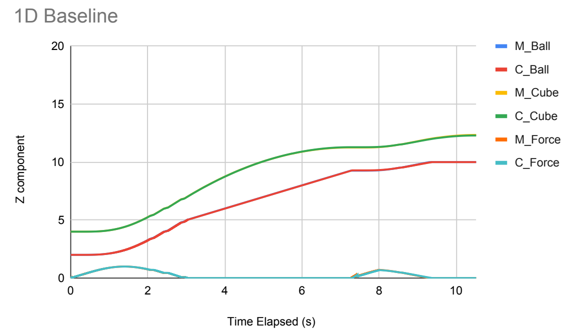
Figure 3: Top-down view of desynchronized master and controlled domains. By giving the cubes different physical properties, they diverge after being pushed around.

the physics engine. 1-dimensional tests became deterministic. 2-dimensional improved as well, except when fast rotations were involved. The exact reason for this behavior was unknown.

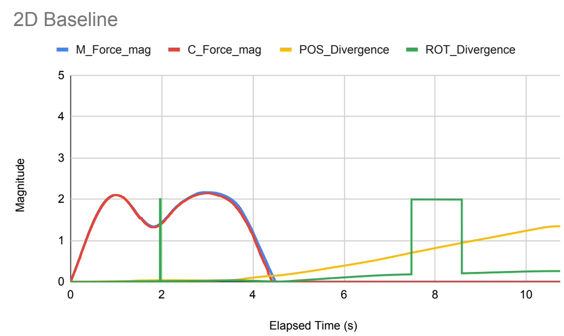
4 Experimental Setup

The following section outlines the experimental setup following the design choices discussed in section 3.

To reduce the 3-dimensional space into a 2-dimensional one, gravity is used in addition to a floor entity, locking all objects on the same Y plane. Furthermore, the shape of every object prevents collisions that would apply forces with a direction outside the Y plane from happening. Finally, using a top-down camera view with an orthographic projection, the 3-dimensional space transforms into a 2-dimensional space. The environment contains a ball that the user can move along the plane using the WASD keys and a block that reacts to applied forces. The two copies are stacked on top of each other. Additionally, the floor separating the copies is translucent so that any desynchronization becomes visible. The experimental setup is depicted in Figure 2.



(a)



(b)

Figure 4: System behaviour in the absence of disturbances. In 1D, master and controlled domains are almost completely identical. In 2D, they diverge a little.

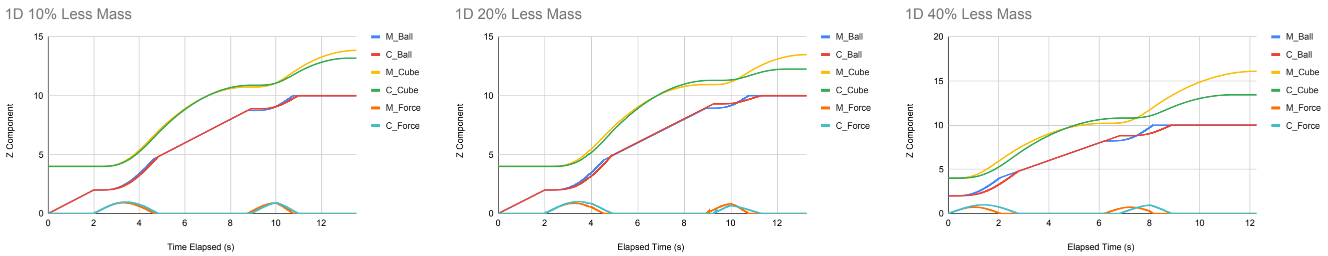
For the 1D application, all objects are positioned on the same line in the new simulated 2D environment and the user can control the ball using only the AD keys. As a result, all collisions result in forces with a direction on that line. In addition, rotations are forcibly disabled to ensure that no object would drift away from that line due to slight imprecisions. With these steps, the 2-dimensional space transforms into a 1-dimensional space.

The programmed paths for the tests are the following. In 1D, the instructions make the ball move a certain distance, pushing the cube along the way. In 2D, the path has the ball move in circular motions while pushing the cube. A baseline test is first performed to verify that the two domains do not diverge on their own. Then, disturbances are introduced, causing desynchronization as can be seen in Figure 3.

Information from every object in the scene is logged with a $1\,\mathrm{ms}$ rate in a .csv file. Position, rotation, and force data are collected this way and then plotted in a graph for visualization. The plots show data from when the first contact between ball and cube happens until the ball has finished its path and the cube becomes static again.

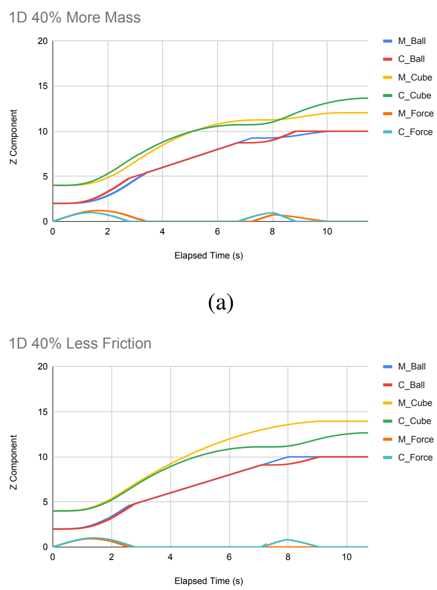
5 Results

Baseline Tests From Figure 4a, we can observe that in the 1-dimensional case, the system is accurate and deterministic. The two physics engines running in parallel produce al-



(a) (b) (c)

Figure 5: Impact of decrease in mass of the master cube on desynchronization. The overall divergence pattern remains the same when increasing the disturbance amount.



(b)

Figure 6: Top is the impact of increase in mass of the master cube. Bottom is the impact of decrease in friction of the master cube

most identical results. The same can not be said about the 2-dimensional case. In Figure 4b we can see that the rotation divergence spikes briefly at 2 s and then longer at around 8 s. These spikes represent moments where one cube starts rotating faster than the other. We can also see that the cubes slowly move away from each other over time. Noticeably, they only truly start diverging after the ball has finished applying force. From this baseline, we can conclude that 2D divergence is information that becomes inaccurate over time due to the non-deterministic nature of the rotations.

Disturbance Amplitude Larger disturbances allow for a clearer overview of the situation. The divergence pattern remains the same but the desynchronization is amplified. In 1D, we can observe that Figure 5a, corresponding to 10% less cube mass on the master domain, behaves similarly to Figure 5c. However, the divergence is minimal in the former and more noticeable in the latter. The research goal is to observe desynchronization. Therefore, further tests are carried out with disturbances of the order of 40%. These results show that disturbances of 10% or less are tolerable and not too bad to correct.

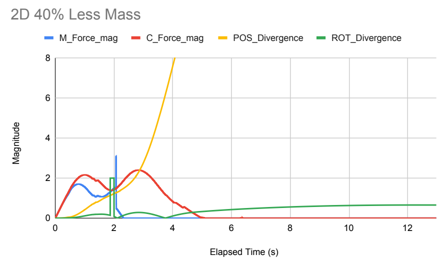
1D When analyzing Figure 5c, up until 8 seconds, the desync is minor. This leaves plenty of time for a complete TI system to reevaluate the mass of the object. The data from the initial push can provide that information. Furthermore, when comparing the final divergence with 40% less mass against 40% more mass (Figure 6a), it can be seen that the latter performs better. In general, regardless of 1D or 2D, for both mass and friction, overestimating has less of an impact than underestimating. Friction mismatch causes divergence to happen much faster when it is underestimated. In figure Figure 6b, the final desynchronization is not significant because the master cube had enough momentum to escape the second push. The divergence would be much bigger if not for the second push given to the controlled cube. In the case of overestimating friction, the results are similar to mass overestimation.

2D The baseline for 2D demonstrates that divergence already occurs without disturbances. In 1D, less friction causes faster divergence than less mass. Looking at Figure 7 it appears to be the opposite in 2D. This is not the reason behind the divergence we see in the graphs. The ball moves in a circle. When the mass is lower, the master cube is positioned during a rotating push exactly on the circle. Then the master cube gets pushed away completely, while the controlled cube stays in the area. This push can be seen in the graph by the blue spike at 2 s. However, in other setups, the desynchronization due to mass mismatch is similar to that of friction mismatch. Not much can further be said about the 2D application due to the non-deterministic behavior.

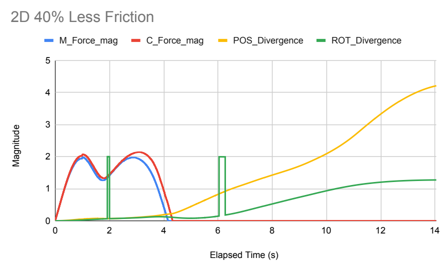
6 Responsible Research

This section discusses firstly the ethical aspect of the work, second the data handling, and last the reproducibility of the results.

Throughout the research process, no data originating from humans were used. No ethical issues arise from this work as it only concerns itself with the observation of a simulation of the real world. The real world, in this case, is a block pushed around by a ball.



(a)



(b)

Figure 7: Top is the impact of decrease in mass of the master cube in 2D. Bottom is the impact of decrease in friction of the master cube in 2D.

The data of a test originates from the full logging of the path. The only data points that were left out were the starting ones before contact is made between ball and cube. No useful information can be found there and has therefore been removed. Efforts were made to make the system as deterministic as possible, which was achieved for 1D, less for 2D. In this work, there is no favorable outcome. The goal is to gain insight into desynchronization and build a framework to build upon. Nothing is gained from trying to get a specific outcome out of the non-deterministic 2D rotations.

This paper details every step concerning the setup in section 4 which should ensure good reproducibility. However, to exactly recreate this work, access to the TI demo that was used as a foundation is necessary. Depending on the physics engine, one should observe not exact but similar results using another system.

7 Future Work

A couple of problems were encountered during this work that can be solved by continuing work on the Tactile Internet system that it builds upon. The issues were mainly the lack of a communication network and the non-deterministic aspects. Further research into a more developed TI system will allow these tests to be performed with greater accuracy. Additionally, it will unlock more simulations to test and analyze.

One interesting observation that resulted from the 1D tests was the length of the time frame during which the two domains would not diverge significantly despite the disturbances. A correction method could take advantage of that time period to reevaluate the situation.

8 Conclusions

Overcoming ”the 1 ms challenge” through simulation using point clouds is still in its infancy stages. Desynchronization between the master and the controlled domains was inevitable and unstudied. The experimental setup of this work provides a framework in which tests can be performed to observe the effects of certain disturbances. Additionally, the simulation can be used to test correction algorithms. Obtained results provided insight into the divergence between master and controlled domains depending on the disturbance introduced. With the current state of the system, the options were limited. In this report, friction and mass mismatches were analyzed in depth. Underestimating the value for mass or friction resulted in higher desynchronization than overestimating them in a 1-dimensional environment. The divergence in 1D also happens slowly in the case of mass and friction mismatch. The lack of a network component blocks the simulation of packet reliability disturbances. Non-deterministic behavior limited the 2-dimensional observations. Further research into this topic can expand the possibilities for research into correction algorithms for desynchronization.

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