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Development of User Interfaces for an Internet-Based Forklift Teleoperation System with Telepresence

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Abstract

Teleoperated systems are often used for operations in difficult and dynamic environments, where remote humans must take over machinery for more difficult or more variable tasks than the local operators or automation system can manage. We designed and developed a prototype internet-based forklift teleoperation system using a real Pallet Carrier in order to augment operation of the Carrier with remote human control, to either assist a local human operator, or to augment or share control with an automatic driving system . We designed the teleoperated forklift system as an exploratory investigation based on telepresence technology that requires a wide field of vision, binaural sound, haptic feedback, and low latency of data transmission. We used the Player robotics platform and Gstreamer to send control information, such as video, audio, and haptic feedback, over the internet. A PS3 controller is used for user input to the system and also provides haptic feedback in the form of the rumble pack. We tested it with a real Pallet Carrier.

Fig. 1. Pallet Carrier, which is a platform of our forklift teleoperation system.

1 Introduction

The internet environment is not a new world anymore and is an indispensable part of our lives. We are using several electronic appliances that are interconnected within the existing Internet infrastructure, and robotics technologies are no exception. Ubiquitous robot systems were developed several years ago for integrating robotic technologies with technologies from the fields of ubiquitous and pervasive computing, sensor networks, and ambient intelligence [Kim *et al.*, 2007]. Similar to ubiquitous robot systems, Cloud robot systems were developed based on cloud computing and take advantage of the rapid increase in data transfer rates to offload tasks without hard real time requirements [Hu *et al.*, 2012; Roboearth].

Although robotic technologies have made remarkable progress, there are still difficulties in some areas especially in providing context awareness and more advanced decision making. Many tasks executed easily by humans turn out to be very difficult to accomplish with a robot. A teleoperated robot system is a semi-automated robot system which allows a human to perform more difficult tasks. Teleoperated robots are often used for operations that must be made more accurately or where the operator must be remote. One application is medical robot systems, such as telemedicine robots [Luo *et al.*, 2009] and surgery robots [Sun *et al.*, 2007; Kummer *et al.*, 2010].

Other applications include operations in hazardous or remote environments where humans cannot be present and the machinery must therefore operate without a local human operator, such as nuclear power stations or military environments [Kang *et al.*, 2005; Fisher *et al.*, 2009; Chang *et al.*, 2011; Everett *et al.*, 1999], and space and deep sea operations [Wilde *et al.*, 2013; Yoon *et al.*, 2004; Soylu *et al.*, 2010; Karras *et al.*, 2009].

Teleoperated robots are used for convenience in our daily life as well. Home automation robots control home appliances as well as managing home status, such as temperature, phone calls, and visitors [Ahn *et al.*, 2009; Yoshimi *et. al.*, 2004]. This makes it possible for humans to monitor home status remotely via the teleoperated robot. Service robots in unmanned environments do daily work instead of human workers, whereby a human teleoperates the robots instead of being at the work place [Ahn *et al.*, 2008]. Teleoperated robots are used for entertainment purposes, for example a receptionist [Hashimoto *et al.*, 2007], newscaster [Ishiguro, 2007], singer [Ahn *et al.*, 2011], and actor [Ahn *et al.*, 2013].

However, the environment of the teleoperated robot can be difficult to understand for the human teleoperator. It is vital for humans to have a high level of situation awareness in many application areas [Johansson *et al.*, 2009]. Therefore quality of teleoperation should be seriouly considered in order to ensure the effectiveness for teleoperated robots, so that control actions are maintained reliably across the network connection, where packet loss and dropped connections are common, and so that sensory feedback is accurately communicated to the human operator and provides an understanding of the working environment of the remote robot. To maintain the quality of operation, it is very important to give rich information about the robot's working environment, and telepresence can help.

Telepresence is the transfer of human senses to remote locations by feeding back sensory information from the remote environment [Elhajj *et al.*, 2001]. It is the enabling of human interaction at a distance, creating a sense of being present at a remote location [Walker *et al.*, 1999]. Telepresence increases the efficiency of teleoperation by giving a more realistic feeling of remote presence [Elhajj *et al.*, 2001]. We need several things to archieve this, such as multi-modal sensory information with visual, aural, and haptic data, a user interface, virtual environment, and a stable network [Emharraf *et al.*, 2012; Rhee *et al.*, 2007; Walker *et al.*, 1999; Kammermeier *et al.*, 1999].

In this paper, we report on the design and development of a forklift teleoperation system with telepresence that allows a remote operator to effectively operate the forklift while maintaining situational awareness. We use a Pallet Carrier shown in Fig. 1, which would usually be used in a pallet packing role, being operated by a single person who drives the forklift, stopping to add product from storage to the pallet. To ensure effective remote operation, we designed a telepresence user interface with multi-modal sensory information including visual, aural, and haptic data. Effective operation means the forklift effectively manoeuvres around its environment regardless of the state of the connection. For this, we evaluate how the forklift is able to operate under normal levels of network latency without loss of control.

This paper is organized as follows. In Section 2, we describe system requirements for our forklift teleoperation system. In Section 3, we introduce the system design. We present the development of our system focusing on telepresence in Section 4, the development of our system focusing on data transmission in Section 5. Finally, we conclude this paper in Section 6.

2 System Requirements

Forklift vehicles are used for carrying and moving objects in factory or logistics environments. In the future forklifts may be automated for normal operations. However there will be some tasks that require special attention from a human driver, such as recovering a forklift from an unexpected location. Teleoperation must enable successful completion of such tasks. In creating the teleoperated forklift system, careful attention was given to the requirements of teleoperation, telepresence, and safety. In order for a remote operator to effectively control a forklift system, a sense of presence needs to be developed. The human teleoperator needs to receive feedback in order to confidently operate the forklift to a similar degree as a local operator. The requirements are a wide field of vision video, bianural sound, haptic feedback, and low latency of data transmission.

2.1 Wide Field of Vision (FOV) Video

An important aspect of telepresence is having a form of visual feedback that conveys enough information to the operator so that they do not feel like they are missing out on visual information. Humans have a very wide field of vision, approximately 210 degrees [Atchison *et al.*, 2000], compared with cameras which have a much narrower field of view, with typical values ranging from 60 to 80 degrees. Having a narrow field of vision reduces the operator's perception of the environment meaning it may be hard to gauge the full surroundings of the forklift. Having a wide field of view is necessary for an effective teleoperation system. Humans are also able to easily look around and are not constrained to a fixed point of view. In addition, video with low resolution means the operator of a teleoperated system would miss out on the fine details of the video and not be able to be fully immersed in the environment. Therefore, video with high resolution is needed as this is more similar to human vision.

2.2 Bianural Sound

Binaural sound allows humans to discriminate sound sources based on their three dimensional location, allowing humans to localise audio sources even when they are out of view. Replicating this ability in a teleoperation system will lead to increased levels of immersion, allowing the operator to control the forklift with more confidence by allowing them to be aware of dynamic elements in their environment. Audio can alert the operator to elements in the environment that they need to be aware of and having directional sound helps in allowing the operator to locate the source of the sound and direct their view to that area if needed. Audio can also be used to give feedback to the user about the state of the forklift they are operating. Each forklift has typical operating sounds such as the noise of the drive and steering motors and if and unusual event happens, audio feedback helps in identifying this.

2.3 Haptic Feedback

One of the important needs for successful teleoperation and telepresence is haptic feedback to the operator. A human greatly relies on the sense of touch and feel to control how they interact with the environment as well as the forklift controls. Haptic feedback, which can correspond to different sensory information, considerably increases operators' efficiency and makes some tasks feasible [Anderson *et al.*, 1992]. The haptic information corresponds to not only actual physical forces, but also other sensory information, such as heat, radiation, and distance to obstacles [Elhajj *et al.*, 2001].

2.4 Low Latency of Data Transmission

Low latency in the actuation of input commands and in feedback being delivered to the user is also vital to the success of of a teleoperation system. It is also very important to maintain a high level of safety. High latency between an input command being sent to the forklift and the required action being performed, or high intersensory latency, the time difference in the same event being experienced by two different senses, i.e. the time difference between seeing an event in the video feed and hearing it in the audio feed, can cause large difficulties in effective teleoperation. If large delays are present, the system can become unstable and it becomes difficult to complete a task in an effective manner [Xia *et al.*, 2012]. An input to feedback latency of 100ms to 200ms and an intersensory delay of around 20ms are the maximum acceptable time delays before a human operator becomes aware of a delay in the system [Delaney *et al.*, 2006].

3 System Design

We have implemented a forklift teleoperation system on the Pallet Carrier utilising two computers communicating over an IP network and a microcontroller hardware interface. The system provides low latency video and audio through four web cameras, and haptic feedback to the operator through a Sony PlayStation 3 (PS3) controller, which is used to transmit the user's commands back to the forklift. Fig. 2 shows the system architecture of our forklift teleoperation system, which consists of a laptop sitting on the forklift, an Arduino microcontroller interfacing with the forklift controls, four cameras with fish eye lenses with one camera sitting on a pan tilt mount, a PS3 controller for user input and a desktop computer at the remote location. Player [Player] is used to send control commands from the remote desktop to the laptop. Gstreamer [Gstreamer] is used to transmit the video and audio from the lift truck to the remote PC.

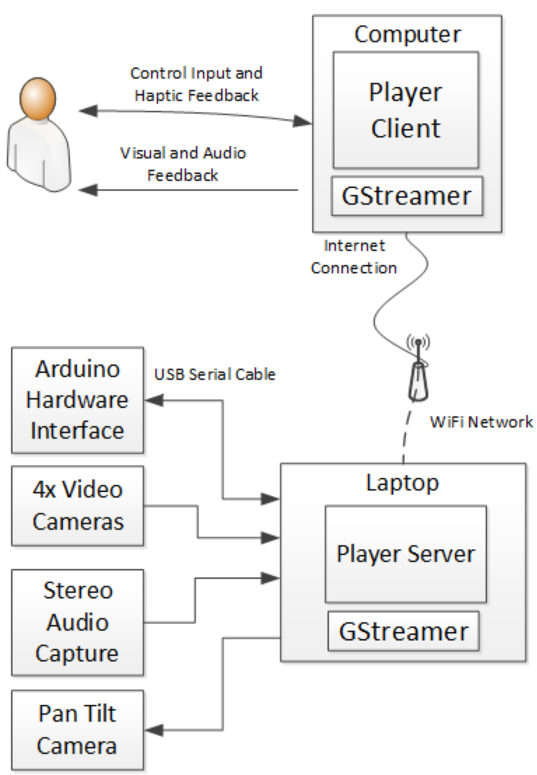


Fig. 2. System architecture of forklift teleoperation system, which consists of a laptop, an Arduino microcontroller, four cameras, a PS3 controller.

3.1 Operating Forklift

In order to understand the needs for teleoperating the Pallet Carrier experience was gained driving it around a simple course performing basic manoeuvres and tasks such as picking and placing a pallet. This provided valuable insight into how the forklift responds to control inputs and how the forklift moves. The Pallet Carrier has a single drive wheel at the front and two castor wheels at the rear under the forks as shown in Fig. 3. This means the centre of turning of the forklift is at the rear between the two castor wheels. This allows the Carrier to be very manoeuvrable but introduces difficulties for teleoperating.

The following needs were identified from our experience with the Pallet Carrier: a wide Field of Vision (FOV) video, seeing down the side of the forklift, and ability to see around the forklift. A wide field of vision is required in the direction of travel so obstacles can be detected and a path planned for travel. When avoiding and driving around obstacles it was necessary to see down the side of the forklift and this is where most of the attention was placed. This is due to the way the Carrier turns about the rear wheels. The ability to see around the forklift at all times to plan movement and be aware of hazards such as people and other forklifts.

3.2 Control Interface

A PS3 controller conveys the user input for controlling the forklift teleoperation system. The PS3 controller was the best fit to all of the requirements and also had the extra benefit of wireless Bluetooth connectivity. Replicating the Carrier's controls was also considered a good fit for the requirements and this option would have been best for increasing the levels of telepresence (would make it feel more like driving the actual forklift).

When connected to the computer either through USB or over Bluetooth, the PS3 controller provides a standard Linux joystick interface, which can be read from in the Player client program. To get the rumble pack haptic feedback to work the PS3 controller must be connected over Bluetooth. The Linux rumble interface works by allowing different rumble actions to be prepared, such as a constant vibration with certain magnitude, and to be played and stopped with a simple API indicating the action to be started or stopped. However this does not work for a constantly changing rumble magnitude. Instead the constant rumble mode is enabled and the magnitude set to the required value.

3.3 Player

The Player robotics platform [Player] is used for the communication between the remote computer and the laptop. Player is an open source platform allowing for the design of robot control programs which can communicate of the IP network. Player uses simple message passing

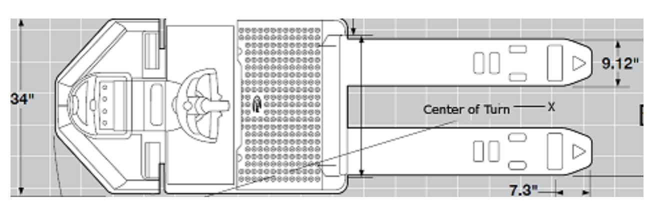


Fig. 3. Illustration of the Pallet Carrier layout.

interfaces with different interfaces being used to communicate different aspects of robot control. Player based systems are separated into the client and the server. The server runs on a computer on the robot while the client runs at a remote location sending control information to the server and receiving feedback the server receives from the robot. To control the forklift, we developed a player server which is executed on the laptop on the forklift and a client running at the remote location.

The client program is used for reading data from the PS3 controller and sending the information to the player server. The client is run in two threads; a thread for the main control and a thread to read data coming from the controller. The main control thread runs in a loop calling the read and update functions for communicating with the server. The controller thread reads the events from the controller, such as a button being pressed or released, an analogue value changing, and stores the relevant information in a structure.

The server program is used for controlling the forklift. The server receives data from the client program and communicates the correct control information to the microcontroller over USB. The Server processes the messages sent from the client and formats the control word that is sent to the microcontroller. The microcontroller expects a 32 bit control word with 11 bits used for throttle, 11 bits used for steering and one bit for each of the digital inputs that leaves 5 bits unused for future expansion. Feedback regarding the actual wheel angle is read from the microcontroller and used to control the pan tilt camera and is sent back to the client. The client uses the value of the actual wheel angle to set the rumble magnitude of the PS3 controller based on the difference between the current user input for steering and the actual wheel angle. These two values can be different as the driver is able to easily move the analogue stick on the controller very quickly while the wheel takes time to rotate.

4 Telepresence

In order to create a successful system, we considered that telepresence includes a wide field of vision with high resolution video, binaural sound, and haptic feedback.

4.1 Video

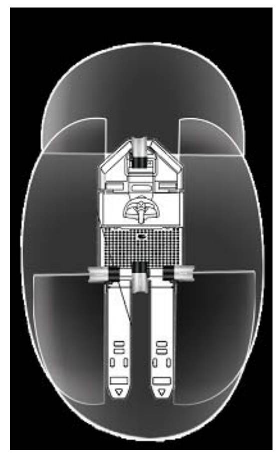
4.1.1 Cameras

Microsoft LifeView Studio web cameras were selected due to their compact form factor, high resolution (1080p) image sensor, USB connectivity and integrated microphones. Four cameras were selected to give optimal coverage of the forklift's surroundings. The Microsoft camera's stock FOV is only 75 degrees however, this is much less than the required FOV for our system. To correct this a bracket was designed and 3D printed in order to retrofit a 180 degree fish eye lens to each camera. While achieving the desired FOV, the fish eye lens introduces the characteristic distortion associated with high FOV lenses. It has been shown, however, that a remote teleoperator is able to effectively control a forklift while viewing wide FOV video [Shiroma *et al.*, 2004]. After retrofitting the cameras with fish eye lenses, a full 360 degree view of the forklift's surrounding was achieved as showned in Fig. 4.

4.1.2 Video Streaming

GStreamer is an open source multimedia framework, operating on multimedia pipelines and supporting a wide range of codecs and media input/outputs. We have selected GStreamer to transmit and receive our video streams based on these features. UDP and TCP transport layers were tested for suitability in our system. TCP was found to deliver reliable video with no packet loss and no noticeable delay relative to UDP and was ultimately selected as the transport layer in our system. While UDP is typically used in time critical systems as it theoretically delivers packet data faster than TCP, we found that video packets were regularly lost - interrupting the video stream and rendering the forklift unusable, as shown in Fig. 5.

The x264 implementation of the H.264 codec has been chosen to encode the video streams based on its support for low latency encoding. Typical encoding involves two types of frames; key frames which include the full scene and are much larger, and b frames which include only the difference between frames. This requires the transmitter to store multiple frames before transmission. x264 provides support for striping the key frame across multiple b frames, reducing the latency before the encoding system can transmit, resulting in a claimed 10ms latency excluding transport delays.



(a)

(b)

Fig. 4. (a) 360° video coverage around the PC4500, (b) video feedback layout.

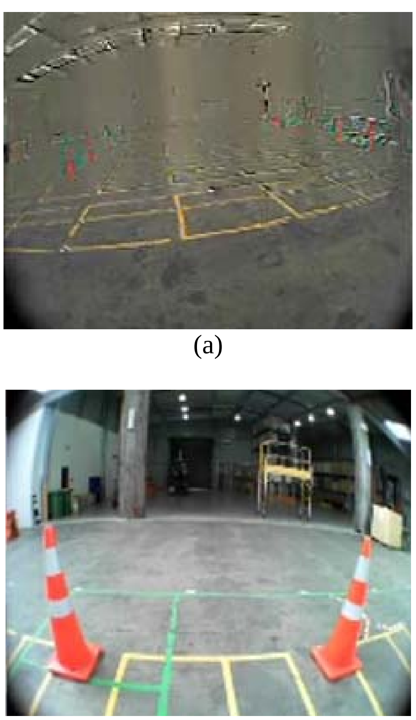
4.1.3 Pan-tilt System

A pan-tilt system has been implemented on the frontfacing camera, supplementing the high FOV camera by allowing the user to freely look around their environment. By default the pan-tilt camera is slaved to the angle of the steered wheel, indicating the operator's current heading by keeping it centred in the driver's view. The driver may optionally unlock the tilt component of the camera only while the forklift is stopped, freely adjusting the view to focus on an area of interest, before locking the tilt of the camera to that height and continuing driving. The driver is required to stop the forklift and hold a combination of buttons to trigger the tilt, ensuring that accidental adjustment does not distract the operator. The pan-tilt system improves the operators FOV increasing the immersion.

4.2 Sound

Audio and subsequently directional audio are important in increasing the situational awareness of the operator especially in a dynamic environment. Audio can alert the operator to elements in the environment that they need to be aware of and having directional sound helps in allowing the operator to locate the source of the sound and direct their view to that area if needed. Audio can also be used to give feedback to the user about the state of the forklift they are operating.

In our system, stereo audio has been implemented in order to give the operator some degree of sound localisation, improving situational awareness. GStreamer was again chosen to implement audio for similar reasons to those mentioned in section 4.1.2. A stereo audio source has been created from the two sidefacing camera's microphones and interlaced in GStreamer so that the operator can listen to the audio through normal stereo headphones or speakers. The relatively new audio codec, Opus, was selected for it's combination of high-fidelity sound reproduction and low latency performance, combining the speech oriented SILK codec as well as the low latency, general purpose CELT codec to provide low latency, high quality audio to the remote operator in order to improve immersion and situational awareness. TCP was selected as the transport layer for delivering audio to the operator, ensuring accurate sound reproduction to the user.



(a)

(b)

Fig. 5. 176x144 front facing (a) UDP camera stream view, (b) TCP camera stream view.

4.3 Haptic and Data Visualization

The last need for successful teleoperation and telepresence is for haptic feedback to the operator. A human greatly relies on the sense of touch and feel to control how they interact with the environment. The Pallet Carrier itself has magnetorheological haptic feedback built into the steering and this allows the user to feel the position of the drive wheel even though there is no physical connection between the steering and the wheel. We used the vibration of PS3 controller for haptic feedback from the forklift.

To supplement the rumble feedback in the controller, we developed a visual dashboard, which displays the actual wheel angle, shown in Fig. 6. The needle on the dial represents the current wheel angle being reported back to the player client from the server and microcontroller. Also displayed on the dashboard are the states of the inputs from the controller. The analogue inputs are displayed with the values being displayed ranging from -1024 to 1024, the actual values the player server and microcontroller expect. The digital inputs (horn, brake, forks up and forks down) are displayed in white while not pressed and turn red while pressed as can be seen with the horn. The dashboard was made as part of the Player client program written as a separate class using the Allegro C++ gaming library.

5 Data Transmission

5.1 Safety

As our forklift weighs 1600 kgs and operates in a dynamic environment shared with pedestrians, safety should be considered in the implemention of our system. A cyclic redundancy check (CRC) is performed on serial data transmitted between the server and hardware interface, and inherently performed on socket communication as a part of the TCP transport layer. The CRC is designed to detect a high percentage or errors and when errors are detected, triggers retransmission of data in socket communication while triggering the forklift's brakes in serial communication. Additionally, the hardware interface triggers a hardware timer to ensure that updates are received periodically and that lag does

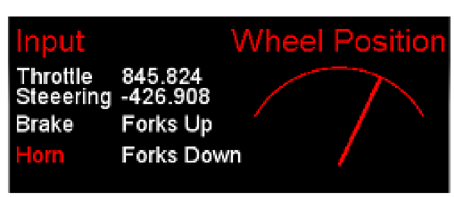


Fig. 6. Visual Dashboard.

not become greater than a threshold, again, triggering the forklift's brakes and making the system safe until latency returns to acceptable values.

For safety reasons, a supervisory driver remains on the forklift during all our tests. While the Carrier is under remote control, the supervisor retains the ability to trigger the forklift's brakes by: stepping off the platform, pressing the brake switch, braking with a remote glove or turning the forklift off with the key. Safety reviews were undertaken after any change to the system, testing that the forklift still functioned as expected and that no safety features had been disabled. Notably, our safety implementation and periodic testing ensured that the supervisor driver did not need to intervene at any point during testing.

5.2 Latency Tests

We have tested our teleoperation system by remotely operating the forklift across 10 km in a city. Communication of Player control data achieved an average round-trip-time of 110ms with 80ms of that time being consumed internally within the system as shown in Fig. 7. Sporadic spikes in latency caused the system's safety features to activate the forklift brakes, ensuring the forklift was only controllable when the operator had real-time knowledge of the forklift's state. Haptic feedback was successfully implemented, indicating to the driver when the steered wheel lags the input.

Additionally, a simple pallet moving task has been successfully completed in which a previously unseen course is navigated by a remote operator, engaging a pallet in a simulated isle and transporting it to another location before disengaging the pallet and returning to the beginning of the course. The remote operator was able to complete the task 15 seconds slower (1 minute 35 seconds vs. 1 minute 50 seconds) than the same operator completing the task while manually controlling the forklift.

6 Conclusions

We designed a teleoperated forklift system over the internet and based on a Pallet Carrier. We considered the requirements for effective teleoperation and telepresence; a wide field of view in the visual feedback, audio feedback, haptic feedback, and low latency in the system for safety. The system consists of a PS3 controller for user input connected to a computer at the remote location. Player is used for communication to a laptop on the forklift. Four cameras have been placed on the forklift with fish eye lenses giving a 360 degree view around the forklift. Stereo audio is also captured from the forklift. This video and audio is transmitted back to the user using GStreamer with low latency video and audio codecs X264 and Opus. Safety considerations were made when making the system such as using a CRC to validate the data being sent to the microcontroller and the forklift's brakes automatically being applied if the latency in the network connection becomes too high.

We tested our teleoperated forklift system for checking latency of data transmission from any remote location over an IP network. From the tests, we expect that our system meets the requirement of enabling a remote driver to be as efficient as a local driver. Our teleoperated forklift system showed it can be used in a real environment and easily controlled by human operators. Currently the only form of feedback from the forklift is the steering angle of the wheel. So we will add other feedback such as speed and fork position in future. Also we plan to increase the effectiveness of the visual feedback using a 3D head mounted display, which helps increase the user immersion in the remote environment.

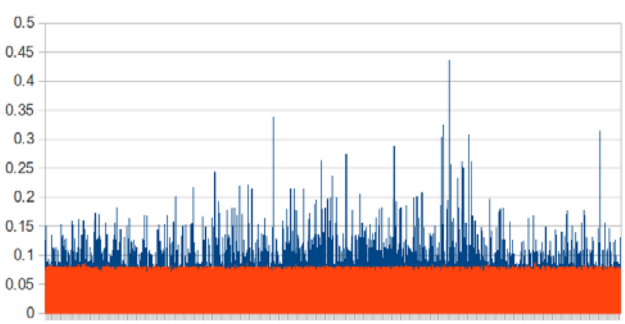


Fig. 7. Control system average round trip time latency. Localhost shown in orange, across-Auckland shown in blue.

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