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Enhancing depth cues with AR visualization for forklift operation assistance in warehouse

by

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Abstract

With warehouse operations contributing to the major part of logistics, architects tend to utilize every inch of the space allocated to maximize the stacking space. Increasing the height of the aisles and narrowing down the aisle-aisle space are major design issues in doing so. Even though forklift manufacturing companies introduced high reach trucks and forklifts for narrow aisles, forklift operators face many issues while working with heavy pallets. This thesis focused on developing a system that uses Augmented Reality (AR) to aid forklift operators in performing their pallet racking and pick up tasks. It used AR technology to superimpose virtual cues over the real world specifying the pallets to be picked up and moved and also assist in operating the forklift using depth cues. This aims to increase the productivity of the forklift operators in the warehouse. Depth cues are overlaid on a live video feed from a camera attached to the front of the forklift which was displayed using a laptop to the participants.

To evaluate the usability of the system designed, an experiment was conducted and the performance results and the feedback from the participants was evaluated. A remote controlled toy forklift was used to conduct the experiment and a motion tracking system was set-up to track the cab and pallet. Simple pallet handling tasks were designed for the participants and their performance and feedback was collected and analysed. This thesis shows how AR offers a simple and efficient solution for the problems faced by forklift operators while performing pallet handling tasks in warehouse.

Contents

Chapter 1

Introduction

Logistics is one of the areas which contributes a great percentage of the economy, but where the innovation is very limited. This may be due to the costs incurred in installing new technology and compensating if there are any setbacks in doing so. Even by providing suitable information to the warehouse-based forklift operators in real time, details about pallet and vacant rack locations and other forklifts positions, warehouse operations can be made more efficient.

Augmented Reality (AR)is technology that allows the real time overlay of virtual imagery onto the real world. It has many applications including entertainment[29], education[19][9], medicine[7], engineering[16][19], navigation[14][8][10] and advertising[1]. Vehicle navigation is one of the areas where AR may provide a great deal of advantage over more traditional techniques such as using maps, or GPS applications on mobile phones. Automotive AR could enhance the driver's experience by showing a new way of overlaying information in the driver's field of view. This project is particularly focused on exploring how AR could be used to assist with forklift navigation and increase performance and ease of operation in the warehouse environment.

AR for education[1] AR for engineering[2]

AR for navigation[3] AR for advertising[4]

Figure 1.1: Applications of AR

Warehousing is one of the critical links in the supply chain. Six issues have been identified as the challenges in warehouse navigation[5]:

1. *Inventory Accuracy*- This is related to database mismanagement where the inventory information is not recorded properly which results in unexpected inventory build-up or shortages.

2. *Inventory Location*- Since warehouses are huge, the operators may lack insight into the inventory location to be picked from or delivered to which results in slow operation.

3. *Space Utilization/Warehouse layout*- Inefficient warehouse layouts cause confusion, increased labour and costs.

4. *Redundant Process*- Most warehouses have an order of operation workers have to follow. For example, they may have to pass a pink ticket and documentation through multiple hands like checker, stager, loader etc. resulting in considerable amount of delay.

[5]http://www.apptricity.com/press/five-common-challenges-in-warehouse-management-and-how-to-overcome-them/

5. *Picking Optimization*- Warehouses which operate manually normally doesn't have a common route taken to pick items for shipment.

6. *Forklift operation*- There are different scenarios where the forklift operation efficiency reduces like varying light conditions, pallet racking or picking in high racks and cold storage warehouses etc.

Many recent forklifts like Crown RM6000 series[6] have cameras available as an accessory to the forklift. Companies like Holland Vision systems[7], Park logistics[8]and GCA equipment[9] sell forklift mount cameras which aim at giving operators better view of the fork and the view in-front of it. The camera system provides additional information on the location and orientation of the

Orlaco camera system[10]

A viewtech camera system installed into a Lindt truck[11]

Figure 1.2: camera systems installed on forklifts

forks, but the depth information cannot be obtained from just the camera view. In this thesis, we are going to investigate how far the camera and depth cues are useful and which interface is preferred the most. The research done as a part of this thesis is going to address the issues of pallet picking and racking tasks especially in high racks and cold storage conditions. The problems related to these issues are discussed in detail the following sections.

[6]https://www.youtube.com/watch?v=Z-6tL4UOE1k
[7]http://hollandvisionsystems.com/lift-truck.php
[8]www.parklogistics.co.uk
[9]http://gcaequipment.com/camera-systems/

Chapter 2

Background

This chapter explains and explores the existing background literature on the technology we are going to use to address the issues faced by the forklift operators in the warehouses. It briefly explains about the depth perception of the humans, depth cues and Augmented Reality as application of warehouse management.

2.1 Depth Cues

Depth estimation has always been a topic of great interest in computer vision. We perceive depth using many features called cues[1] which are defined as any statistic or signal which explains about any property of image or object of interest. Cues used by our visual system can be classified into many groups based on many properties. They are broadly classified as binocular and monocular.

Binocular Cues

The uniqueness and beauty behind construction of two eyes in humans can be seen when we look at people who have faulty vision. A just born baby who has fault with one eye cannot absolutely perceive depth. Most of the work done in the area of depth estimation is based on stereo-

[1] http://www.colorado.edu/physics/phys1230/phys1230fa08/VisualCues.pdf

vision. The concept of binocular vision which is, capturing same scene with slight variation in viewpoint, is used to estimate depth. Firstly, two images are captured with a slight variation in view point and the correspondences are estimated which may be point, line or region and using triangulation method, the depth of the scene is estimated. Many algorithms were proposed based on the type of correspondences chosen to triangulate the disparity[22]. So binocular cues are necessary to learn depth and distance estimation. These cues are:

1. **Stereopsis** is the most important cue used by humans to perceive depth[4]. Eyes are constructed such that there is a small horizontal distance called *disparity* between our eyes. When an image is projected on to both eyes there is a small parallax difference and using this fact the brain has the capability to perceive the depth of the image.

2. **Convergence** is a binocular occulometer cue[6] used to perceive depth. When we want to fixate on an object near to us, our eyes converge and when we fixate on objects very far away, eyes diverge to maintain fixation. The feedback from these eye muscles provides some information about the distance to the object. This is effective for smaller distance below 10 meters, since it's very difficult to make angle of convergence of eyes smaller inorder to fixate eye on far objects.

3. **Shadow Stereopsis** doesn't use horizontal parallax but stereoscopically combines different shadows to impart depth perception[18].

Monocular Cues

Even though we need binocular cues, in order to estimate relative depth and motion, monocular cues plays great role since they provide depth and motion information even though we use only one eye. Some of them are

1. **Texture Gradient** is a cue used to estimate the relative distance. Texture is the regular repetition of an element or a pattern. As we see from Fig2.1 as the texture explosion and variation increases the depth of the scene seems to increase. We can observe the same

where there is nearly uniform texture like forests or fields where as depth increases, the texture gradient increases.

2. **Motion Parallax** is a cue used to estimate when objects in the scene are in motion. Objects having less depth seem to move faster than objects far even though they have same velocity.

3. **Aerial Perspective** is predominantly used to find whether objects are far because the faraway objects seems to be blurred and hazy, and the examples are mountains and sky.

4. **Linear Perspective** can be seen predominantly when we see lot of lines like edges and corners in an image. Parallel lines tends to meet at some distance.

5. **Curvilinear Perspective** cues captures the property of curving of parallel lines at the edges of the visual field which greatly improves the perception of 3 dimensional space.

6. **Overlap or interposition** cue is used to explain relative depth when one object overlaps other. Usually the object overlapping the other is perceived to be near.

7. **Relative Size** cue typically explains how objects of the same size looks smaller when they are far away.

8. **Lighting and Shading** is an effective cue to determine depth when the variation of light and shades. As we can see from 2.1, when the light strikes an object which is near, it looks brightest and its shadows are created on the objects that are far. This imparts a sense of depth variation in the scene as in Fig2.1.

9. **Defocus Blur** cue is commonly used to establish impressions of depth in an image. Except the object of interest, the image is made out of focus to impart sense of depth which can be observed from Fig2.1.

Relative size[2]

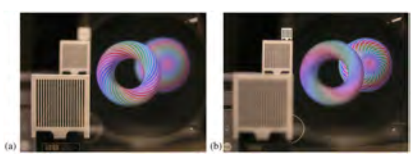
motion parallax[3]

Texture Gradient[4]

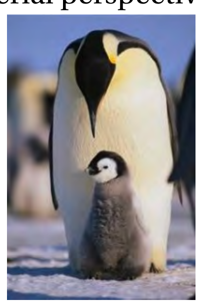
Linear perspective[5]

Aerial perspective[6]

Curvilinear perspective[7]



Focus cues[8]



Overlap[9]

Lighting and shading[10]

Figure 2.1: Monocular Cues

2.1.1 Vision guided forklift operation

Vision guidance is mostly used in forklift automation industry to navigate and for pallet engagement. In general, stereo vision is used to estimate the scene depth value and scene understanding. In their Tele-robot system, Yamada and Muto[28] used a stereo camera to measure the distance to the task object in the field of view. They have used the images taken by the camera to provide the left, right and top view images of the task object to virtually guide operator.

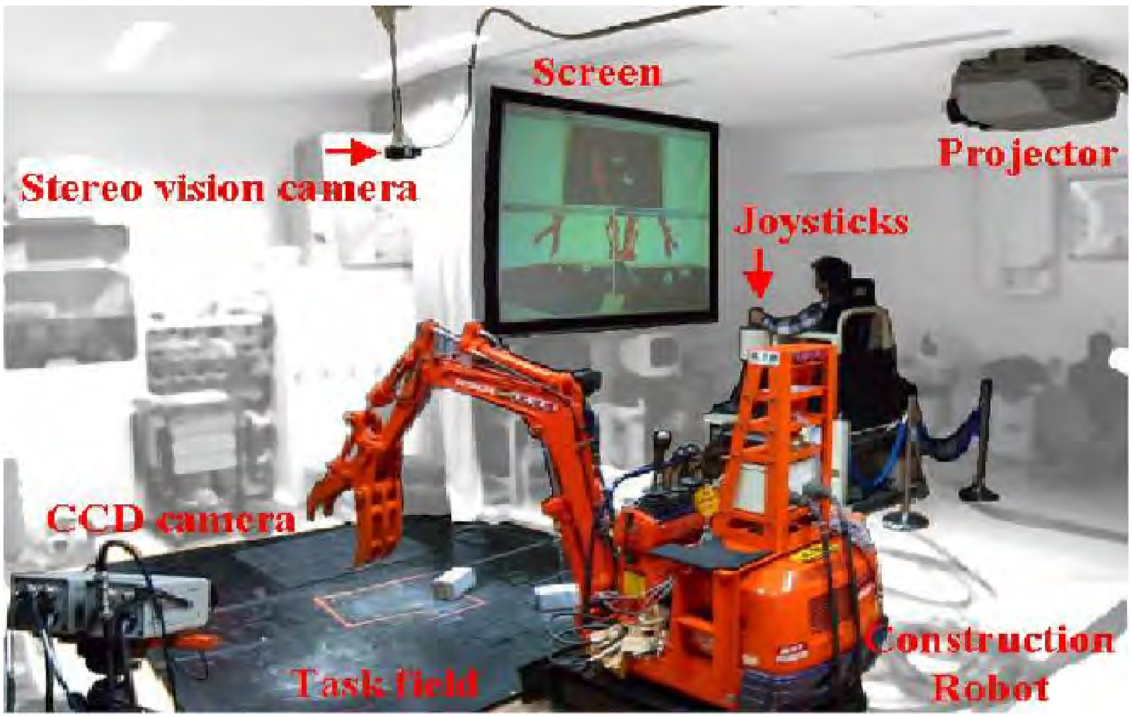


Figure 2.2: Arrangement of system[25]

Seelinger and Yoder[25] used a vision guided control system for mobile manipulators. They have developed a system which is used to automatically engage pallets once the forklift operators reach the destination aisle. However, this system requires at least two cameras to recognize the pallets and calculate the distance between the forklift and the pallets. Two types of experiments were done, one using fiducial to recognize the pallet and the other using natural features. Though the forklift engaged the pallet 98 times out of 100 trials, while using natural features the surroundings were cleared out of other objects.

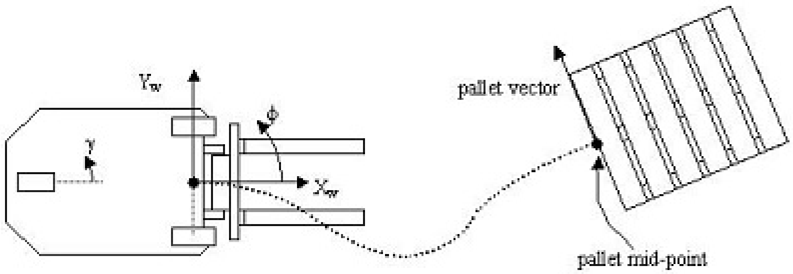


Figure 2.3: Autonomous path planning and pallet engagement[2]

Baglivo et al.[2] worked on autonomous pallet localization and picking using computer vision techniques for pallet slot recognition and dynamic path planning. They used natural edge, line and corner features to recognize pallet and to divide the slots and to calculate the centrist. Pose of the pallet is estimated to engage the pallet even in cluttered background. When tested in varying light conditions with objects geometrically similar to the pallets lying around the pallet, the system failed to identify the pallet.

However all of the above research has mostly concentrated on autonomous pallet recognition and picking. This research concentrates more on performance increase in the forklift operation during pickup tasks when information about the pallet and fork locations are given to the operators.

2.1.2 Augmented Reality

Augmenting or overlaying virtual imagery over a real world can be termed as Augmented Reality (AR). According to Azuma[1] AR must have the following key attributes

- Combine virtual information with real world.
- Contain a 3D relationship between the real world and digital information.
- Be interactive and visualized in real-time.

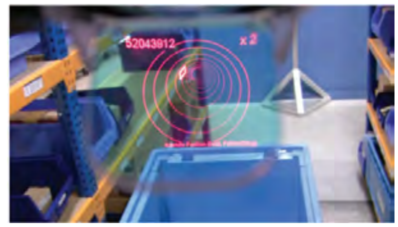
Augmented Reality is related to Virtual Reality (VR), though there is a key difference in that VR aims to immerse the user in a Virtual world rather than augmenting virtual objects in the real world like AR.

2.1.3 AR for Order Picking

The gathering of goods from locations in a warehouse according to the customer's needs is called order picking, and is one of the most complicated problem in logistics. Traditionally, order picking is performed by people moving around the warehouse shelves using a picking list printed on paper. Many techniques have been introduced to improve efficiency including order picking using handheld scanner, using lights on the target bins and using voice input[23]. However some of them have disadvantages, like increasing the time taken or poor performance due to a noisy environment.

There has also been some previous research on the use of AR for order picking. For example, Schwerdtfeger et.al[20][23][21] developed an application to pick up orders using vision. Two types of pick by vision methods were proposed, one using a hand held PDA interface and the other using AR system (Optical see through(OST)HMD). The AR version of pick by vision had two phases which were coarse navigation where the user had to find the right shelf and fine navigation where the user had to find the correct box in the shelf.

Pick by scanning label, by light and voice simultaneously



Pick up vision

Figure 2.4: Picking[20]

They found no difference in picking performance, but in the AR condition subjects took longer to navigate to the pick location. The small field of view and the bad depth perception of the non-stereoscopic HMD caused problems. Most of the subjects could not clearly identify the real spatial position of the virtual arrows pointing on the storage compartment. Thus, they often grasped into the storage compartment above or below the right one.

Figure 2.5: Picking display configurations[5]

A comparison of order picking assisted by heads up display (HUD), cart mounted display, lights and a paper pick list was carried out by Guo et.al[5]. The Pick by Cart mounted Dispaly (CMD) was one of the most efficient and inexpensive ways of order picking, however the user had to turn their heads between the cart mounted display and the picking bins. Pick by HMD was most efficient in terms of time since the information was continuously displayed and the user had no need to turn their head. Pick by light and using a paper pick list had almost no error but the efficiency in time was far less compared to the previous two methods.

A limited field of view is one of the drawbacks of using current HMD's and in order to help users gaze towards the box to be picked from, Schwerdtfeger[24] combined actual picking visualization with meta-visualization.

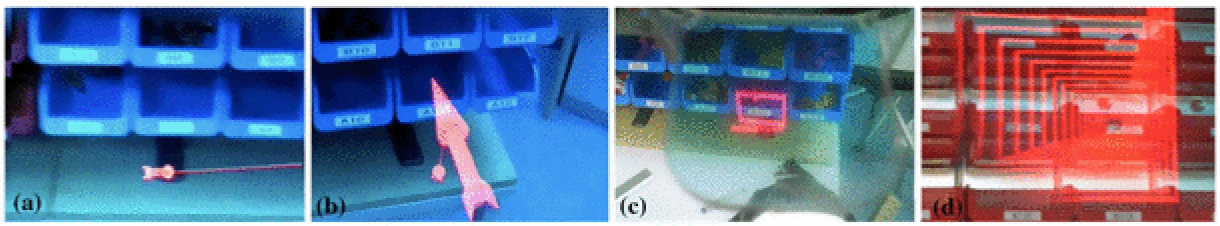


Figure 2.6: Picking Visualization[17] a.The meta-visualization,b.Arrow,c.The frame,d.The tunnel

Sebastian[17] conducted out a comparative study using four different picking conditions, (1) PbP (pick by paper), (2) PbV (pick by voice), (3) PbVi (pick by vision(AR)), and (4) PbPj (pick by projector). The Paper-picking (PbP) condition, a worker picks according to the instructions printed on paper showing the list of items to pick or graphical representation. PbVi needs special equipment like a HMD to visualize the information and a computing device to generate and process the information. PbV requires additional equipment like a headset for input and output and a wearable computer which can process picking information and gives out voice commands. Since the system has to be controlled by voice commands, speech recognition system is required to identify the commands. A projector to project a square over the object to be picked is used in PbPi. The Pick by projector condition was found to be the fastest of all and also took less work-load compared to the other conditions. Although subjective measurements found that the projection method was the most favoured among users, when different error types were considered, the HMD method was the best.

(a) PbPa (b) PbVo (c) PbPr (d) PbVi

Figure 2.7: Order picking conditions[17]

Logistics company DHL[11] reported a 25% efficiency increase in warehouse picking when using smart glasses with an AR interface. The smart glasses also provide a hands free picking process which completely eliminates the need of paper or any other objects[12].
A number of companies have developed concept videos showing how wearable computing and AR could be used in a warehouse setting. SAP and head mounted display company Vuzix partnered together to show how head mounted AR could be combined with a wearable computer and used to aid a forklift operator[13]. Knapp produced a video to introduce their KiSoft Vision software that uses wearable AR technology to improve stock picking . Unlike the SAP, Knapp[14] showed a real working system, however it also has simpler functionality and shows using virtual arrows to assist with navigation, bar code scanning, and visual tracking from physical markers in the real work to identify locations for stock picking. From this research we can learn that the scope of AR in assisting picking process is immense and the improvement of the performance of the operators using AR over traditional methods shows the impact it can make in logistics.

2.1.4 AR for Indoor Navigation

Indoor navigation is one of the most complicated and useful applications of Augmented Reality requiring continues monitoring of the user's location and details about the infrastructure. Many applications[12][11][13] have been developed which use a mobile device's camera feed

[11] http://electronicspurchasingstrategies.com/2015/01/28/dhl-tests-augmented-reality-use-logistics/
[12] https://www.youtube.com/watch?v=I8vYrAUb0BQ
[13] $www.youtube.com/watch?v = 9Wv9k_s sLcI$
[14] $www.youtube.com/watch?v = BWY8uFlteIM$

video and overlay the navigation instructions on-to the display. For example, Mulloni et.al[13] have created an indoor navigation application using activity based instruction with sparse 3D localization at selected points in the building. However the interface was not very effective since there were navigational errors because of the info points which lead to the confusion in the users.

Figure 2.8: Indoor navigation application[12]

Moller et.al[12] have designed a mobile indoor navigation application using vision based localization. Both AR and VR applications were developed and a user study and evaluation was carried out to discover which was better for navigation. Other localization methods-like WLAN does not work well with wide and large environments where AR is difficult to use. Vision based localization is more sophisticated since it can be done by accessing the mobile's camera. Additional combination of other sensors like accelerometer makes this approach more usable than others. Comparing AR and VR, the errors using both interfaces were similar, and users preferred AR rather than VR because of it's reliable localization, but incase of incorrect location and orientation estimation, VR was more reliable[12].

2.1.5 AR for Vehicle Navigation

Possible applications of AR for vehicle navigation has led to research in this area which includes integrating complex tracking methods into hybrid positioning systems.[15]. Narzt et.al[15] have demonstrated how having an additional device to overlay AR information could be annoying to use in day to day life. They have developed an AR application for car navigation where the windshield is used to augment navigation, safety and other details. They also explored the future of Augmented Reality applications for car navigation using windshield, PDA or mobile as display device. Jaguar has unveiled their AR application[15] for car navigation assistance where a ghost car would be displayed on the virtual windscreen so that the driver would just follow the ghost car in front. It has special functions that include traffic signal detection, possible collision or accident alerts, and showing other driver information.

Figure 2.9: Car navigation assistance using ghost car[16]

Research has also been conducted on how information should be presented in the AR view. For example, using a HUD navigation cues could either be presented aligned to the wind-shield or aligned to the real world. In studying this, Todoriki et. al.[26] reported that the recognition time for navigation cues shown in a world aligned way was 60% faster than for a screen aligned cues, and the user needed to look at the display significantly fewer times. Similarly, Tonnis et. al.[27] showed that world aligned AR cues showing driver assistance information significantly

[15] https://www.youtube.com/watch?v=TOHnJa9wACI

[16] http://www.techweekeurope.co.uk/wp-content/uploads/2014/12/jaguar-virtual-wind-screen-get-info-of-th jpg

improved driver performance.

Using a heads down navigation display requires user to take their eyes off from the real world, so a HUD seems to provide more significant performance improvement. Although there have been many advances in navigational assistance, there are still more technical challenges to be dealt with like accurate tracking, and depth perception etc.

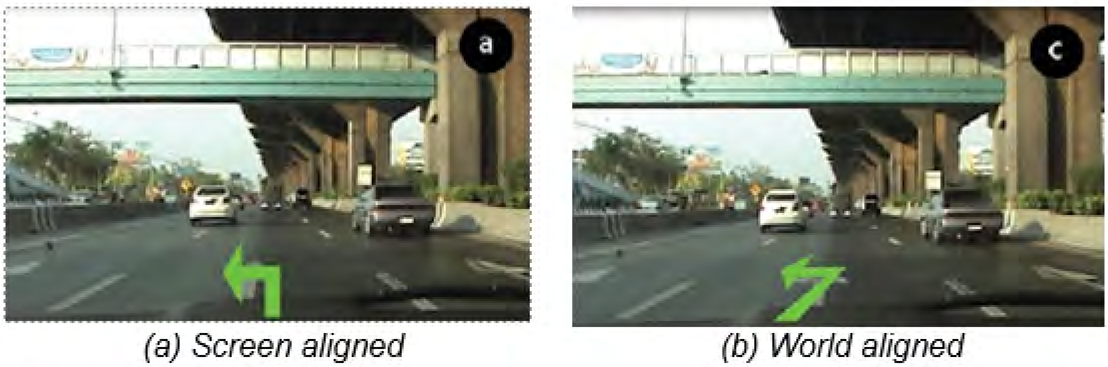
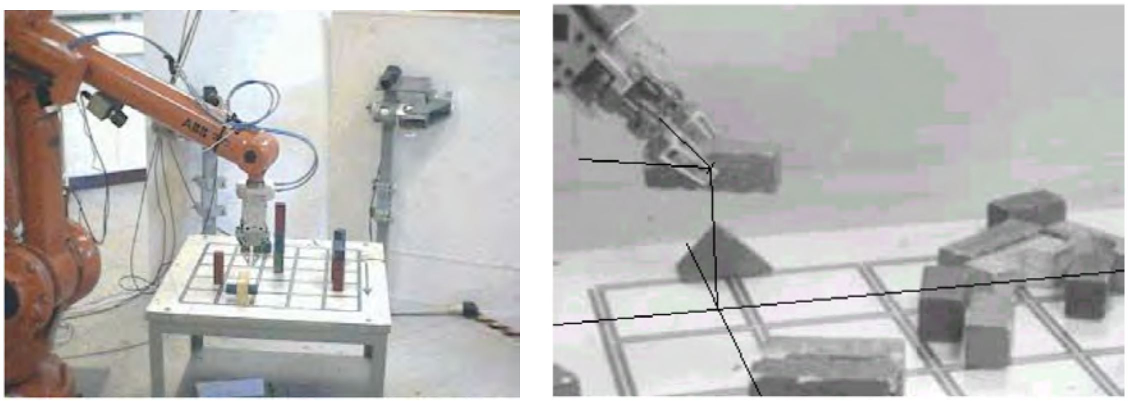


Figure 2.10: Alignment of navigational cues[27]

2.1.6 AR in telerobotics

Friz et.al[3] developed an AR user interface for an internet telerobot named **Usher**. This interface used multiple monoscopic images together to develop a stick figure visualization to improve depth perception of the users.

The stick figure visualization of the robot's 5 dof is overlaid on the monoscopic images which was developed based on Gibson's ecological approach of visual perception. The main aim was to manipulate the robot using simple two dimensional input device like a mouse. The stick cursor was very intuitive and simple to the users and hence there was a drastic change in the depth perception of the users.



Robot picking up the blocks   Usher user Interface

Figure 2.11: Usher[3]

2.1.7 Related Patents

US Patent 2014/0114530 issued on April 2014 describes a vehicle computer system having a transparent display used for navigation and information display in a warehouse. The patent claims relate to using sensor data to modify the information shown on the transparent screen to make it safer to use. For example, if the vehicle is in motion, then only clock information is shown on the display so that the operator is not distracted. When the vehicle is stopped then much more information is shown on the screen to help the operator with good picking.

The patent specifically mentions implementation of a transparent display on a forklift that is used for AR information display, saying "the augmented reality environment could overlay the real-world environment viewed through the transparent display device with graphical and/ or textual data regarding the location of warehoused items to be picked up and the best route to reach their location."

Knapp was granted the European Patent EP20120185761 on May 26th 2014, relating to some of the concepts shown in their video demo. The patent covers the use of a mobile device with an optical see-through head mounted display to assist with object picking in a warehouse, with information about which are to be picked and where the goods are, being shown in the head mounted display. The patent claims relate to the use of an optical display to show an order list

[17] US Patent 2014/0114530

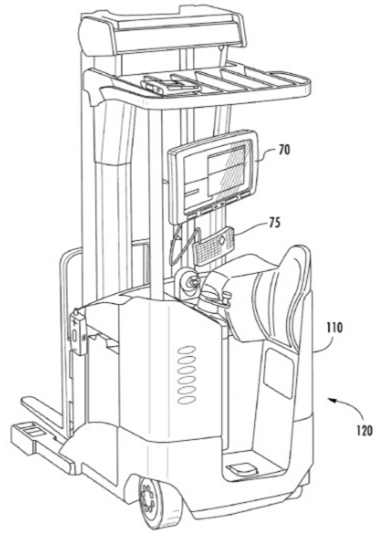


Figure 2.12: Forklift with transparent display[17]

for picking goods in a warehouse and display information about where the goods are located, and placing the picked goods on a driver-less transport vehicle. Additional claims related to the use of marks in the real world, such as reflective symbols, to assist with tracking of the transport vehicle, use of QR codes for detecting goods, and the use of virtual signs shown on the optical display to assist with goods location.

2.1.8 Summary

It is estimated that the picking process alone costs around 55-65 % of the entire warehouse operations. The previous work shows the immense scope that AR has for assisting with navigation and pick up functions.

Previous research has also shown the use of AR in both indoor and outdoor navigation and it's role in assisting drivers. Warehouse operations involve a great amount of path planning and navigation and the extent of the usability of AR in these situations should be studied. Though studies were carried out on the applications of AR in logistics, they mainly concentrated on warehouse operations rather than the forklift operation. Forklift operators deal with pallets which are heavy and hence they have to be extra careful while handling them. Picking and racking pallets at heights require great depth perception and judgement and it is time consuming. This thesis introduces a novel solution to these problems using Augmented Reality.

Chapter 3

User Need Analysis

A site visit was done to the Foodstuff warehouse[1], a local distribution warehouse on 16th July 2015 to understand the operations of the warehouse and to explore possible use of Augmented Reality to improve forklift operations. The visit included overall explanation of the warehouse operations by the warehouse manager. The site manager gave a detailed explanation about the forklift operations and difficulties faced by the operators. We were explained the operation of various types of forklifts and the difficulties faced in operating them. We had opportunity to look at the operation of the warehouse which included forklift operation, pallet database, ordering and shipping of the goods. Findings from the visit could be summarized as the following:

3.0.9 Key Learnings from observation and site manager

- The reach forklifts already have displays and live camera views on them for seeing goods on high rack shelves - this would be suitable for AR augmentation
- The forklift operators receive job instructions from a text based console in the cab, and have to enter job completion details back into the console when done.
- Reach truck operators typically just work in a small area of 1-2 rack aisles (cluster order

[1] http://www.foodstuffs.co.nz/

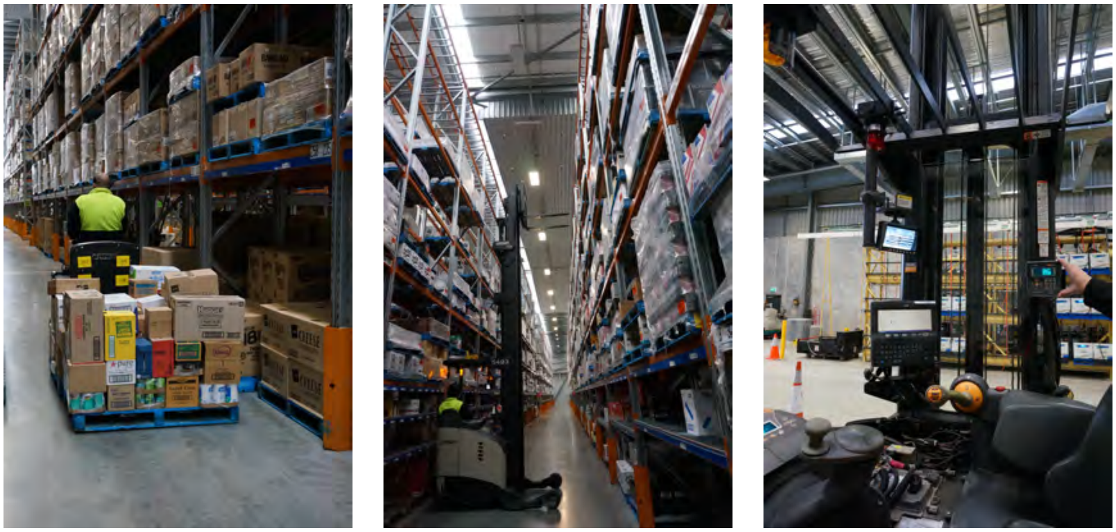


Figure 3.1: Shelves and Reach Forklift

picking strategy). There is not much navigation done over long distances in the warehouse. There is normally just one high lift forklift in any one area at time.

- Although the warehouse has a very sophisticated management system, there is still scope for human errors and delay. For example, when the forklift has to put the pallets into vacant space, there are times when the rack is actually not vacant and the operator has to ask for help to see the next possible vacant rack to fill.

- The order picking and distribution mainly focuses on priority. Although uncommon, the forklifts may have to navigate to different aisles of the warehouse and there is no proper navigation system.

- While replenishment and picking orders by the forklift, the operator had to take down the pallet and scan the label code using handheld scanner.

- Augmented Reality could help improve (i) navigation to aisle location, (ii) put up and take down tasks, (iii) fork in moving pallets safely using additional cues, (iv) training.

Figure 3.2: Foodstuff Warehouse

It was observed that different forklifts have their own specific applications and hence the applications of AR will vary. AR navigation suits Counterbalance and pallet forklifts which are typically driven over a larger area rather than reach forklifts which has less range of movement. However, assisting the operator about movement of the fork using depth cues would be very useful in reach forklifts.

Pallet forklift[2] Counterbalance forklift[3] Reach forklift[4]

Figure 3.3: Different types of forklifts

A detailed interview with the forklift operator was essential to look into possible applications which contribute to the maximum efficiency in warehouse operations. Another site visit was done to the Foodstuff warehouse on 17th August 2015 to do further analysis into the operations of the warehouse and to know precisely where AR could be used to help the operators. An informal interview with the supervisor of the forklift operations and a forklift operator is done to get the further insights into the operations and difficulties faced by the operators and the warehouse management. During this visit, we had a chance of watching an operator demonstrate the forklift operation. The key learnings from the interview is summarized as the following:

3.0.10 Key Learning from the forklift operator

- As the aisles are numbered in an order, the forklift operators can learn location details in a week and there is no much need of navigation aids.
- The camera in the reach forklift is fixed at a particular position and moves with the fork and is used to help with the positioning of the fork for pallet racking at higher rack levels. The display has a green line overlapped on the camera feed so that the operators know where to place the fork, but the operators have to look up to the shelves to make sure of the orientation of the forks.
- To verify the pallets in the upper shelves, the operator have to let down the pallets and verify and if it's not the right pallet, the operator have to verify the other pallets in the same way, since it is not possible to verify the license number without letting them down.
- The counterbalance forklifts transports the wrapped pallets to the loading area and there is not much navigation involved.
- The jiffy or picking forklifts are used to pick-up orders and the operators use pick by voice system.
- A common mistake by the forklift operators is that they misplace the pallets sometimes

when there is no vacant rack where it is supposed to be. There is no verification system where the warehouse management can verify if the operator has placed the pallet in the right rack.

- The most critical task seems to be pallet racking particularly if the pallets are heavy and if they have to be stacked on the higher racks.

Since the aisles are well organized, it was observed that there won't be much need of navigation in this warehouse. However AR can be used to help with the tasks in the reach forklifts for pallet racking, replenishment and verification. Another major issue about the camera feed was that, the camera is fixed to the mast at a standard height on the fork and only moves above if the fork moves above that standard height. Hence, the camera has no use in the lower levels which needs to be improvised.

3.1 Problem Definition

Figure 3.4: High Reach Forklift[5]

The picture above depicts the major problem we are trying to address in this thesis. For high reach forklifts, especially in warehouses having high narrow aisles, the visibility of the shelves and the forks is the major issue. Since the shelves are constructed with great heights, the operator visibility is very limited and it's stressful to judge the relative depth between the forks and pallet to avoid damage to either forklift or the pallets.

This thesis will partially address the visibility issues in cold storage. Though special forklifts are built to regulate the cabin temperatures, since that restricts forklift operators to move and look out of forklift for pallet handling tasks, the visibility is worse. Hence an interface which assists the operators and reduces the need to get out the cabin will be a good solution to this issue.

[5]http://www.fallsway.com/uploads/rm6000s-1.jpg

Figure 3.5: Forklift in a cold-storage warehouse[6]

As seen from the previous site visits, the reach forklifts has a small interface which showed the camera feed with a green line to indicate the shelf level. But it was observed that it was not of much help and hence another site visit was done to the Crown LiftTruck ltd to have a closer look at the reach forklift and to find the possible camera positions that provides maximum view and natural cues. Camera was fixed in various places on the fork and the mast to check the possible best views of the camera. The researcher had a chance to operate the forklift and drive around to have better experience about the visibility issues. From the feedback given by the forklift operator after driving the reach forklift and observations by the researcher, the following details were noted

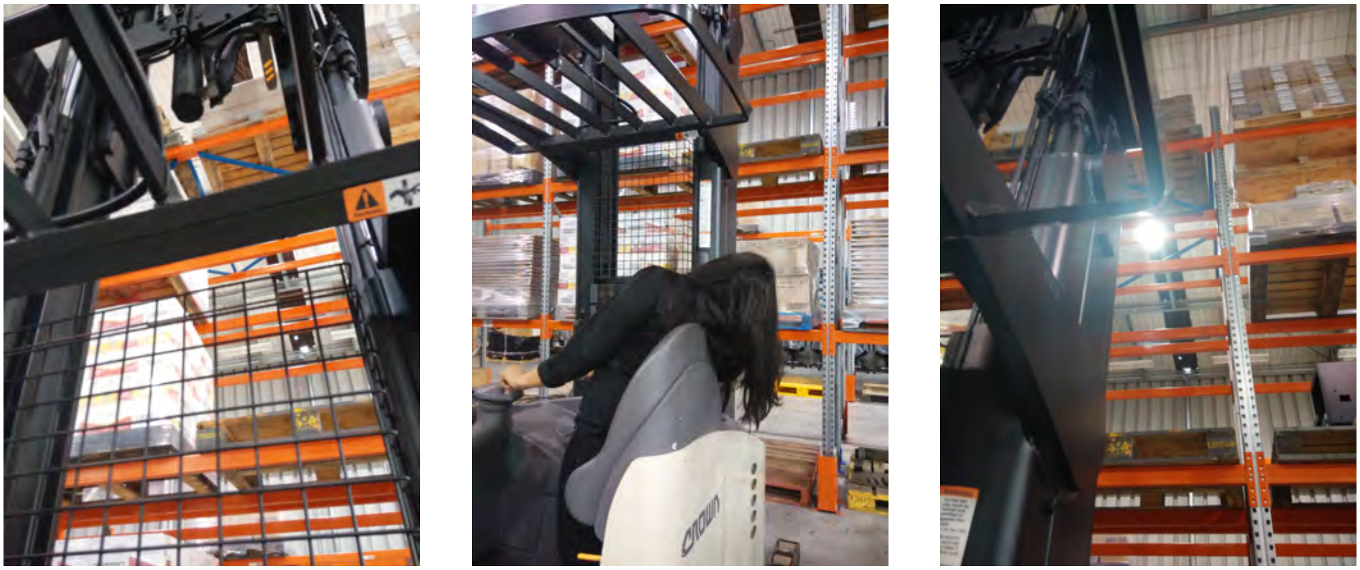
1. The reach forklift blocks most of the view except for a little view towards the right and in the middle.

2. An interface can help operator if it can indicate

   - The distance from the fork to the shelf.

   - The orientation of forks with respect to the shelves.

[6] http://warehousenews.co.uk/wp-content/uploads/2014/06/C127851-Medium.jpg



View from forklift cabin | Researcher leaning to see the forks | View towards right from cabin

Figure 3.6: Shelf view from forklift

- The depth information of the fork relative to the shelves.

3. The location of the empty slot where pallet is supposed to be placed also plays a major role in the ease of the task. If the empty slot is located to the right end of the shelf, the operator can have the pole as a marker such that he/she places the pallet next to the pole.

4. If the location of the empty slot is to the left end or if there are no pallets relative to the empty slot, it doesn't help the operator since the visibility of the shelves towards the left is bad.

Chapter 4

Design Process

Based on the details from the above section, an ideal interface would help the operator if it can

- Show the height of the fork and the height of the empty slot.
- Horizontal orientation of the fork and relative location of the empty slot or pallet to be picked up.
- The depth of the fork in the shelf such that it can place the pallet without damaging it.

This chapter explains the design process from a low fidelity prototype to functional prototype. A low fidelity video prototype was designed first and looking at the limitations and problems faced, another prototype was developed using VR in Unity.

Figure 4.1: Design flow

4.1 Design Considerations

Most of the shelves in the warehouses having enough space to place either two or three pallets. The construction of the shelf is such that the pallets are placed on two horizontal metal rods rather than a rectangular metal slab. So, an additional care should be taken while placing the pallet such that it doesn't fall in between the two parallel horizontal bars.

The main aim in deciding the camera position is that the forks and their orientation data should be clearly visible and visibility of the shelf and the pallet is desirable. One possible position for the camera is to place it in the center of the forks on the mast which works very well when the fork is empty, but when the pallet is on the fork the camera view is completely blocked by the pallet.
Another suitable position for the camera is to place it on the left side of the mast with camera facing towards the fork. This makes one fork visible completely and the other fork partly visible. When there is a pallet on the forks, an edge of the pallet is visible making it easy to place the pallet relative to the shelf.

4.2 Low fidelity Prototype

Through design analysis, we had a definite idea how the interface needs to be. We designed a low fidelity prototype with the pre-recorded videos of camera fixed under the fork[1]. Using this we could better visualize the tasks and the view of the camera. Simple interface designs were created using adobe aftereffects[2] to visualize how the feedback from a system will improve their judgement and make the task less mentally stressful.
In this prototype, we used visual cues and the numbers (height of the fork from ground), since we had an idea that we can take the input of height of fork from the forklift. It was designed to help forklift operators orient the fork and hence, the idea is to give the operators data about

[1] https://youtu.be/ZUuvQBjU5ZE
[2] http://www.adobe.com/nz/products/aftereffects.html

the orientation of the fork and data about the orientation of the pallet. Hence the interface had information about the fork and the pallet with some more visual cues.

Unless there is a picking or racking task to do, the forklift operators lowers fork to a height little

Figure 4.2: Pallet Location Information

above the ground. The figure above shows how the interface displays the task information and the location of the pallet.

Figure 4.3: Fork vertical alignment

The figures above shows how the location of the fork, the pallet of interest and an additional arrow which indicates how far the fork should go align itself when the pallet is displayed. When the fork reaches the height of the pallet, the pallet location is highlighted in green.

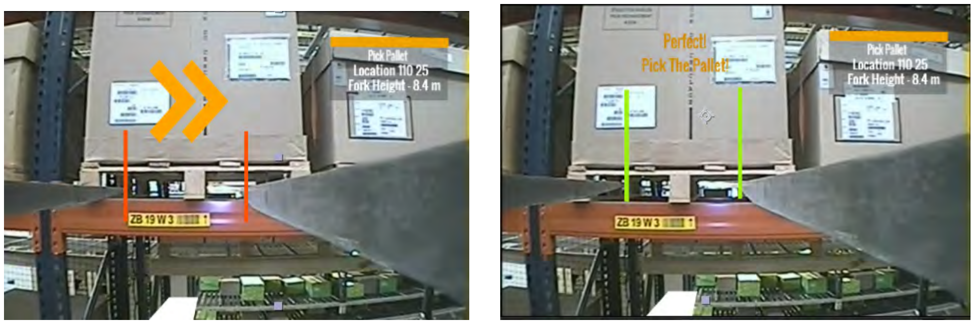


Figure 4.4: Fork horizontal alignment

The figures shows how the forks can be horizontally aligned with the pallet using the arrow. The orange lines essentially shows the location of the forks and when they are in the right position the orange lines change their colour into green indicating the forklift operator that they can move the forks inside the pallet.

Figure 4.5: Depth Cue

The figure above shows how the visual cue essentially indicates the operator how far the fork is and the ideal distance the fork has to move in.

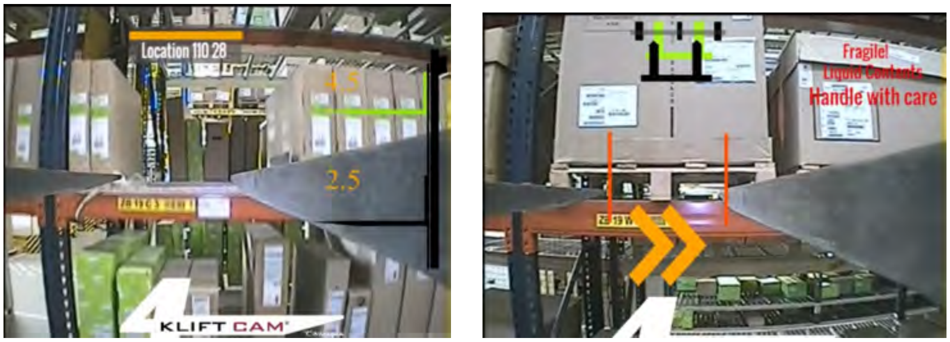


Figure 4.6: Fork horizontal alignment

The figures above has some additional visual cues which were used to estimate the redundant cues and the extent of usability of the interface. Though we felt that all the issues were addressed in this prototype, the interface was not intuitive. It was displaying the information more rather than helping the operator visualize it. Though we had many other ideas of making it more intuitive, they couldn't be realized in this video clip. Hence we opted for VR to do the job of visualization much simpler and effective. We chose a platform where the issues can be viewed and addressed better.

4.3 Prototype in VR

As we have seen in the previous section, the video mock-up helped us study the problems we are addressing, however it was difficult to visualize and address the specified issues. Hence we preferred to design prototype in VR using Unity. Hardware equipment used for prototyping were

1. PC
2. Occulus Rift
3. Joystick

The Occulus Rift was used to visualize the virtual warehouse and the forklift in VR. The joystick was used to navigate the forklift front and back and to move the forks up and down. A similar project was done by *Alexandre Pereira* to simulate a virtual warehouse and to use a forklift to navigate in the warehouse. The same project was used to develop a prototype to visualize how the depth cues would be useful in pallet handling tasks to the researcher.

Occulus Rift[3]

Logitech Joystick[4]

Figure 4.7: Hardware used for prototyping

The design addresses three main tasks.

Fork alignment

From the site visits and the videos, we have observed that the operators have problem judging the level of the forks from the camera feed. For example, even though the operator feels certain height of fork is enough to move forward and slide the forks under the pallet, when the operator moves forward, he/she realises that it is not the desirable height and hence they move the fork up or down depending on the location of the fork. To avoid this confusion, red lines were drawn as the extensions of the fork on to the shelf. They give the operator the precise location where the forks will end up on the shelf if he/she continues to move in the same direction. A horizontal line connecting all the three line extensions from the fork was drawn on the surface of the shelf to improve the visualization of the vertical and horizontal orientation of the forks.

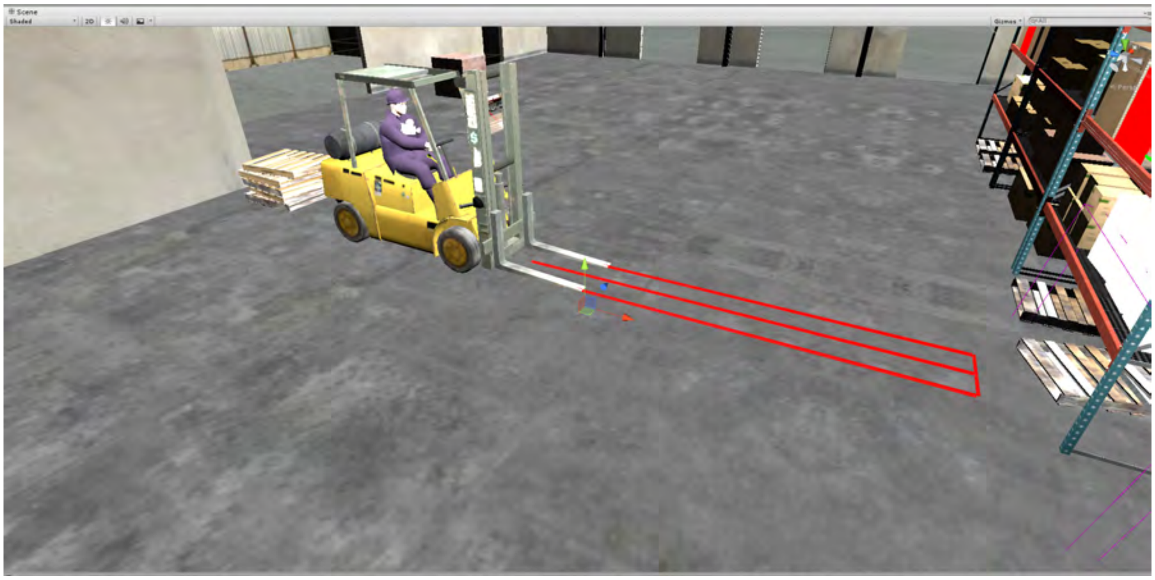


Figure 4.8: Fork line extensions

Pallet Picking

Pallet racking is one of the most important pallet handling task. To align the forks to the pallet, additional cues are provided displayed near the pallet which specifies the vertical and horizontal alignment of the forks to avoid bumping the pallet or shelf. The green horizontal and vertical lines indicate the precise alignment the forks should have to complete the task. As we have

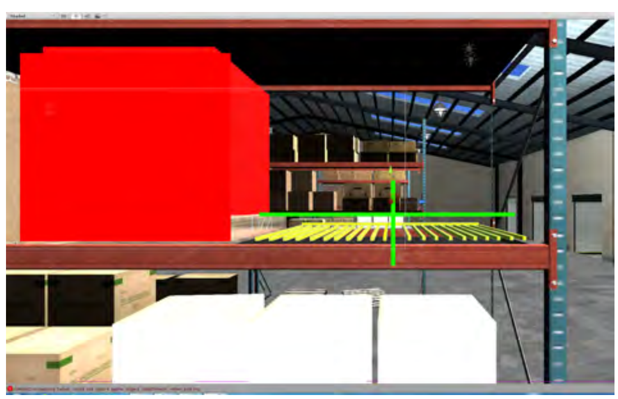


Figure 4.9: Cues to align the forks

noted in the shelf design section before, most of the shelves have two parallel beams on which the pallet has to be placed, hence there is no window for major errors if we don't want to damage the forklift or the pallet. So we designed a depth cue which includes a grid of lines and an indicator which specifies the distance till which the pallet can be moved to pick the pallet without damaging it.

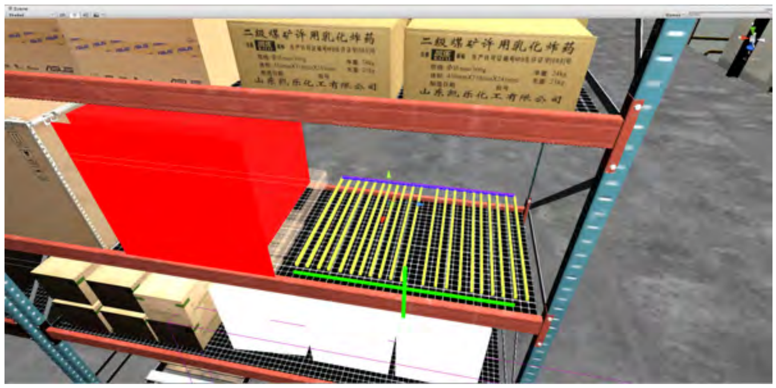


Figure 4.10: Depth mesh

Pallet Racking

This is the most complicated task since when the pallet is on the forks, most of the camera view is blocked by the pallet. Hence we used an X ray vision view to give the operator enough information to complete their tasks. The view in the interface uses shaders to show the location of the vertices of the pallet and the fork extension lines to help operator navigate to the shelf and rack the pallet.

Figure 4.11: Pallet Racking

Cabin View

Even in the virtual simulation, we created a camera texture in the cabin which is similar to the 7 inch tablet that will be used in real forklift.

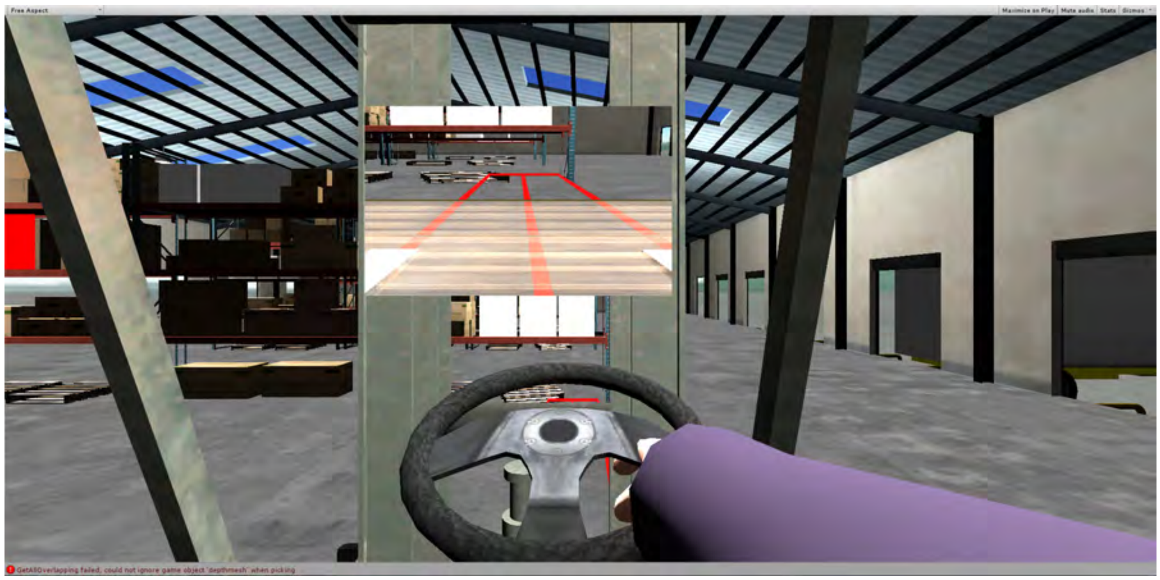


Figure 4.12: Cabin View

The video mock up gave an insight of all possible issues, we would be facing in operating the forklift, but since it's a video taken in another forklift, we couldn't design much. However in this prototype, we had the flexibility of designing the cues and their visualization was easy.

4.4 Summary

A prototype was simulated in VR to visualize the depth cues better in an virtual environment. Care was taken such that all information needed to perform pallet handling tasks was included. In the next chapter we will see how the prototype implemented in VR is scaled to work for an actual real world system.

Chapter 5

Implementation and Functional Prototype

This chapter explains the implementation and various iterations for developing the final robust working prototype. The system is designed to work on the real forklift, however due to limited resources and unavailability of more forklift operators for quantitative analysis, the functional prototype was tested on a toy forklift. However, since the system is designed to be scaled easily on to the real forklift, there wouldn't be much difficulty in implementing this in real forklift.

5.1 Hardware

5.1.1 Toy Forklift

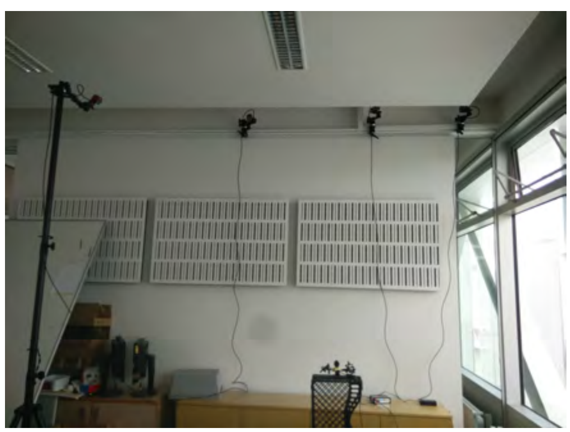
An R/C controlled toy forklift with toy shelves and pallets was used to test the system. It is 1:14 scaled replica reach forklift toy which had controls to move forward, backward, steer and to move the forks up and down.

Forklift[1]

Figure 5.1: Toy Forklift

5.1.2 Motion Tracking system

A motion tracking system using optical motion tracking system was used to track the rigid bodies. The Optitrack system is coupled with Micron series CS-400 Calibration Square, CW-500 Calibration Wand kit[2] can produce 3D data with sub-20 millimetre accuracy in optimal conditions.



Optitrack Motion Tracking[3]

Figure 5.2: Motion Tracking System

Four Flex 13 cameras were set-up to track the volume of the test space. The resolution of the

[2] https://www.optitrack.com/products/tools/

Flex 13 Cameras[5]

Calibration wand[6]

Calibration frame[7]

Figure 5.3: Motion Tracking System

cameras is 1.3 million pixels with 56^0 field of view and 120 FPS sample rate. It is a professional motion capture camera with precision and accuracy[4].

5.1.3 Camera

Microsoft Lifecam studio[8] is attached to the forks to get the real time feed which is given as input to the Unity on which depth cues are augmented. LifeCam Studio has 1080p HD sensor, auto-focus with clear frame technology.

Camera[9]

Figure 5.4: Microsoft Lifecam Studio

[4] 111.optitrack.com/products/flex-13/indepth.html
[8] http://www.microsoft.com/accessories/en-us/products/webcams/lifecam-studio

5.2 Software

Unity

Unity[10] is a game development platform flexible for developing 2D or 3D games or interactive projects. The availability of plug-ins for AR and VR makes it the most desirable game engine for it's sophistication and simplicity. The virtual simulation for the prototype was developed in Unity 4.2.1. The aim of the application while doing the prototype was to simulate a virtual warehouse and a forklift to navigate to the shelves and to do simple pallet handling tasks. Functional prototype was implemented in Unity 5.2.3f1 and the main aim of the application was to get input from the camera and provide appropriate cues on the feed and display it to the user.

Motive

Motive is Optitrack's software platform with various 6DoF rigid body tracking applications. We used Motive 1.9 for this project and utilized rigid body tracking and information broadcasting applications. Once calibrated, the motive tracks the markers precisely which will be attached to

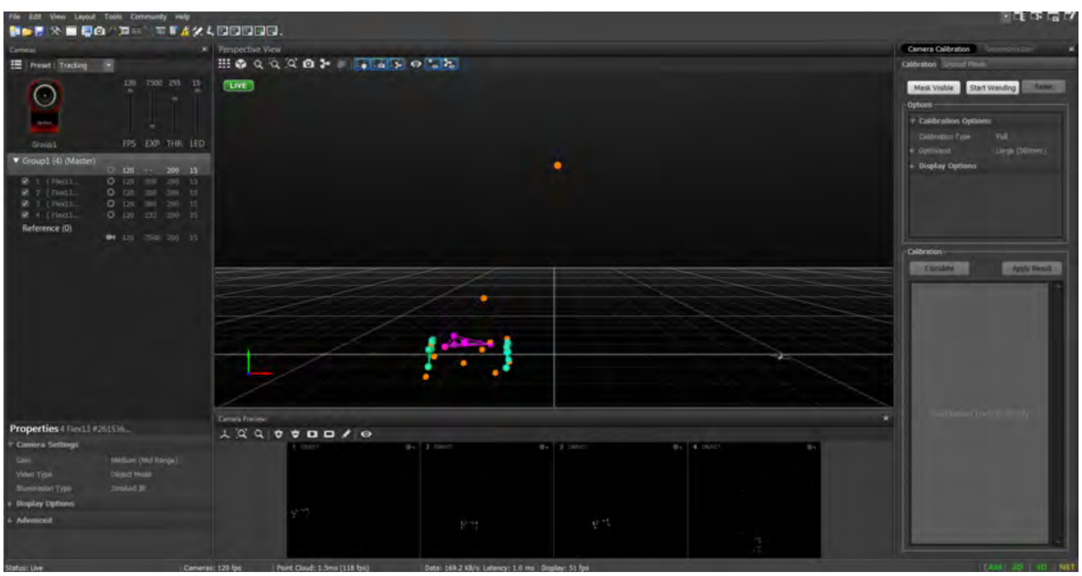


Figure 5.5: Motive

[10]http://unity3d.com/unity

the rigid body of interest. In this project, a calibration frame is used to calibrate the camera with respect to forklift marker. The fork of the forklift is attached with a marker to track the position of the fork. The 3D information about the rigid bodies is broadcast by Optihub[11] to which the cameras and laptop were connected. The motive gives the position and roll, pitch, yaw values of the rigid bodies being tracked. To be able to stream the data into Unity we used NatNet SDK[12] which is essentially a client/server networking SDK.

5.3 System Setup

The entire system consists of a toy forklift with a marker and camera attached to the fork, a toy shelf with a toy pallet, motion tracking system to track forks which gives the 3D data as input to the Unity which is used to augment appropriate cues on the camera feed.

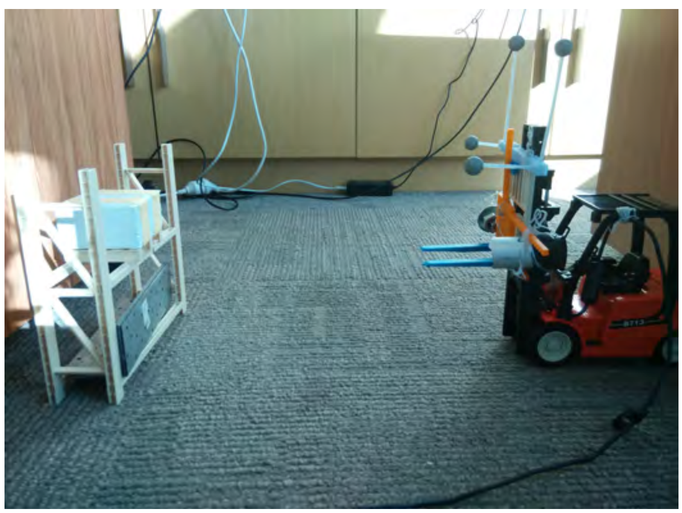


Figure 5.6: Toy forklift with shelf and pallet

5.3.1 Tracking

A tracking marker is attached to the fork of the forklift to track the location of the fork in real time. Though fixing another camera between the two forks is ideal, since we are dealing with a

[11] https://www.optitrack.com/products/sync-switches-hubs/
[12] https://www.optitrack.com/products/natnet-sdk/

small toy, the camera is attached to a side of the fork such that the camera view includes full view of the left fork and a partial view of the right. The idea of setting up the camera in that position is to have some cues about the real world even when the pallet is on the fork which includes a partial view of the end of the pallet so that it can be used as a reference to the shelf while placing the pallet on shelf.

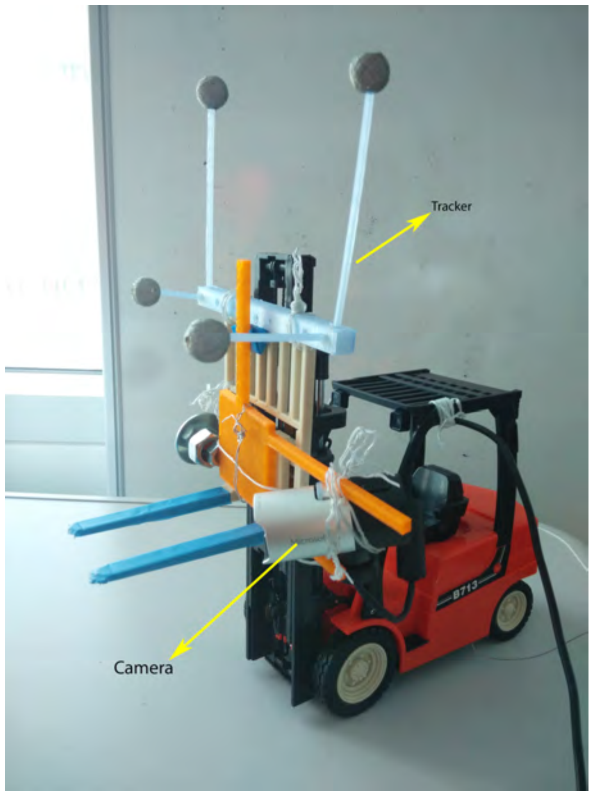


Figure 5.7: Toy forklift and Tracking Marker

5.3.2 Camera Calibration

Camera Calibration is done to compute relative rotation and transformation matrix between the camera mounted and the marker attached to the cab. Direct Linear Transformation algorithmHartley2004 is used to compute the transformation and rotation matrix. The 2D-3D correspondences are noted and then used to compute the matrices. The 2D coordinates are noted from the camera video and the corresponding 3D coordinates of the marker are added from the

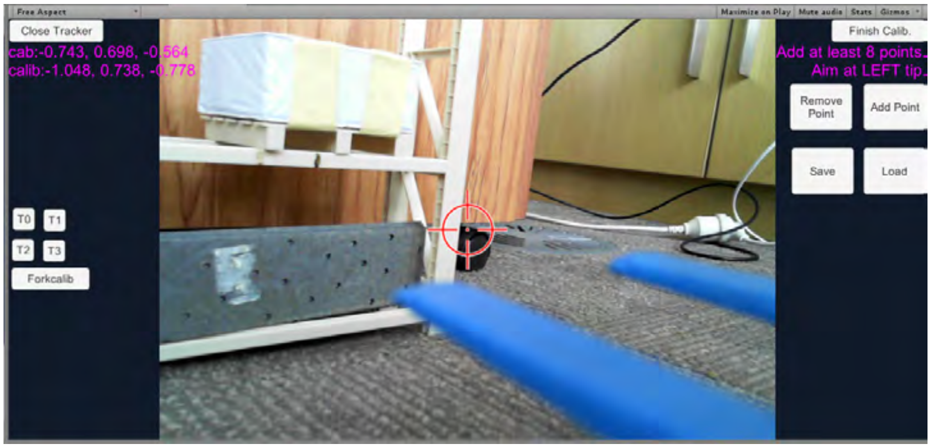


Figure 5.8: Camera Calibration Interface

data output of motive. To compute these matrices, the first step is to get 2D to 3D correspondences and the minimum number of corresponds required is 8.

The figure below shows the interface design for the calibration. To calibrate, we used calibration frame to get 2D and 3D correspondences. In this interface, **Add Point** is used to add the 2D points and store corresponding 3D points from motive. **Remove point** is used to remove the previous 2D-3D correspondence. **Load** button is used to load the previous calibration if it was saved and **save** is used to save the calibration matrix. **Finish Calib** is used to compute the calibration matrix once enough points are added. The figure below shows the design of the interface.

The calibration process is as below:

1. Press calib which displays all the buttons (Add point, remove point, save, load).

2. Place the marker in the camera view and navigate the reticle to point the marker as in the figure below and press **Add point** button.

3. Change the marker into random location in the camera view and add point as above.

4. Minimum of 8 correspondences are required in this process and it is better to add point from random location in the camera view.

5. Compute calibration matrix by pressing **Finish Calib** button.

6. If the error is less, save the calibration.

7. If the error>3, it is better to calibrate again.

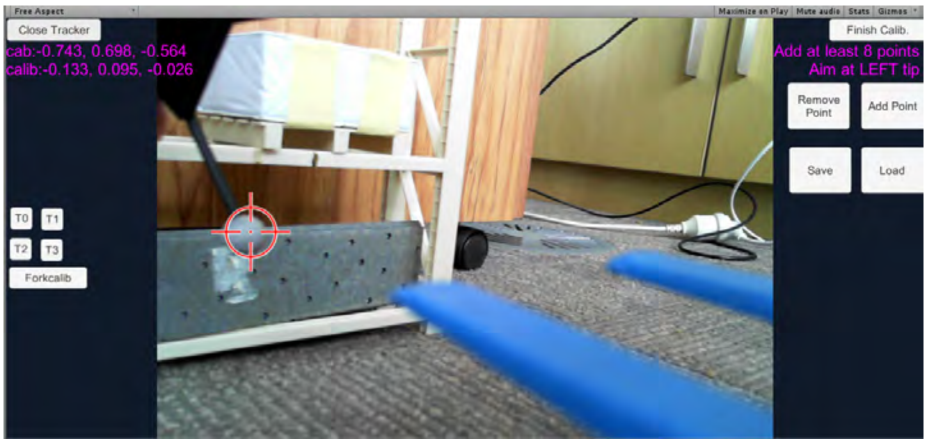


Figure 5.9: Calibrating using marker

5.3.3 Interface Design

The interface design is done based on the previous prototypes which included video mock-up and the Unity project and it is done in three stages for three different tasks.

Fork Alignment

To align fork with pallet to avoid bumping we need to take care of both vertical and horizontal orientation of the fork. For this a marker is augmented on the pallet which gives the information about the height and horizontal orientation the fork is supposed to have not to bump into the pallet. The blue horizontal and vertical lines gives the information about the orientation of the pallet. Green extension lines are drawn from the fork extending upto the surface of the shelf. A horizontal orange line connecting the extended fork-lines is drawn to give some more perspective of the fork alignment.

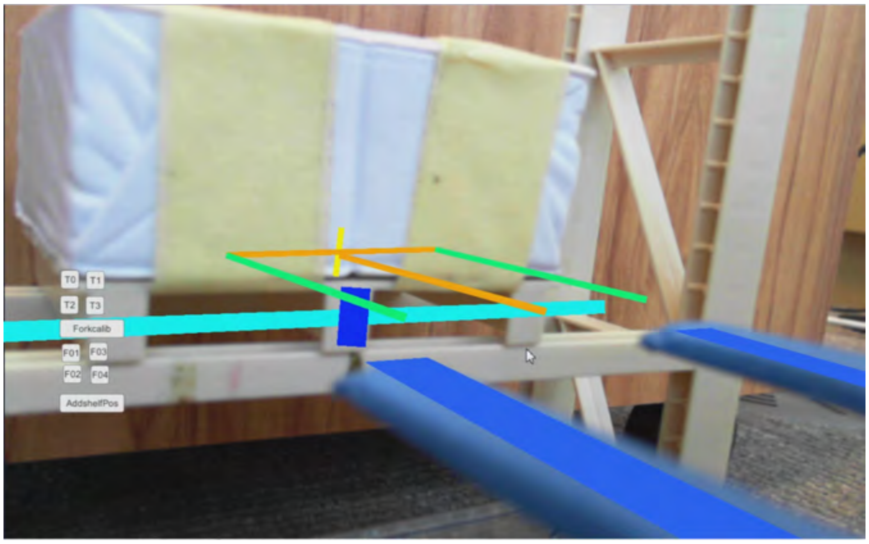


Figure 5.10: Pallet Marker

A vertical yellow line is drawn on the surface of the shelf located at the end of the middle line to give information about horizontal orientation.

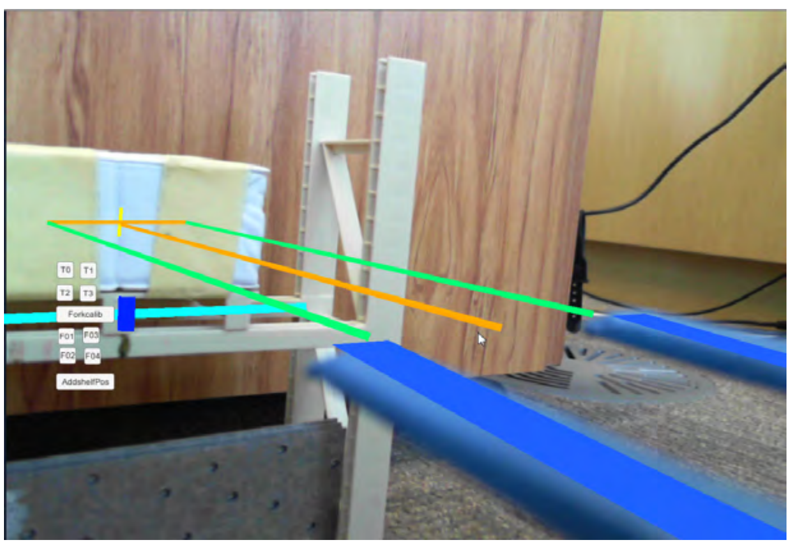


Figure 5.11: Fork Lines

The length of the green lines indicates the distance between the fork and the shelves. The decrease in the length of the green lines indicate that the forks are getting closer to the shelves and if the length of the green line is zero, then we can infer that forks are on the front surface of the shelf. The yellow vertical line gives information about the horizontal orientation of the fork. Ideally if the orange horizontal and yellow vertical lines matches with the blue pallet marker then the fork is in right position to move in without bumping into the pallet.

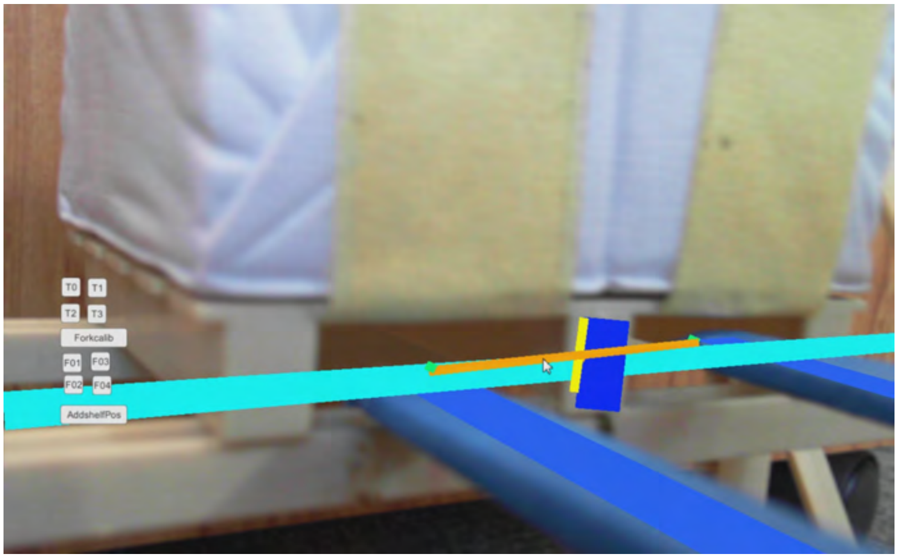


Figure 5.12: Fork alignment

5.3.4 Pallet Picking

To pick the pallet, the operator has to slide the forks inside the pallet enough to lift the pallet up. If the forks are moved too deep or too shallow, the pallet has a chance of falling down once picked up. Hence, some information about how deep the forks can go would be very useful to judge how deep forks should go. In order to give an idea of the location of the fork even when they go inside the pallet, blue virtual quads representing the real forks are shown to provide x-ray vision like visualization are augmented on the real forks. A green line is displayed indicating the depth near or till which the forks can slide in to pick the pallet up without damaging them.

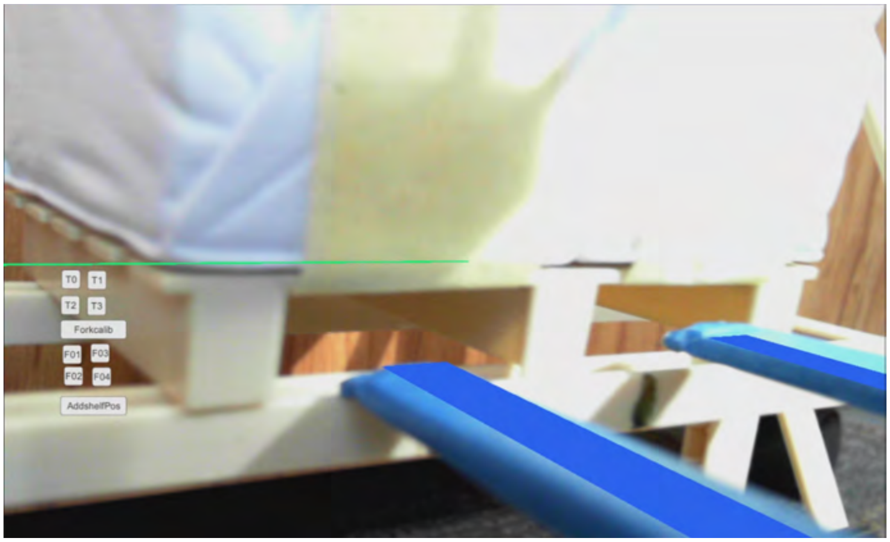


Figure 5.13: Augmented forks

The blue quads are augmented over the real forks and hence the operator can know the exact location of the forks even they are inside the pallet and the camera view is blocked. The green

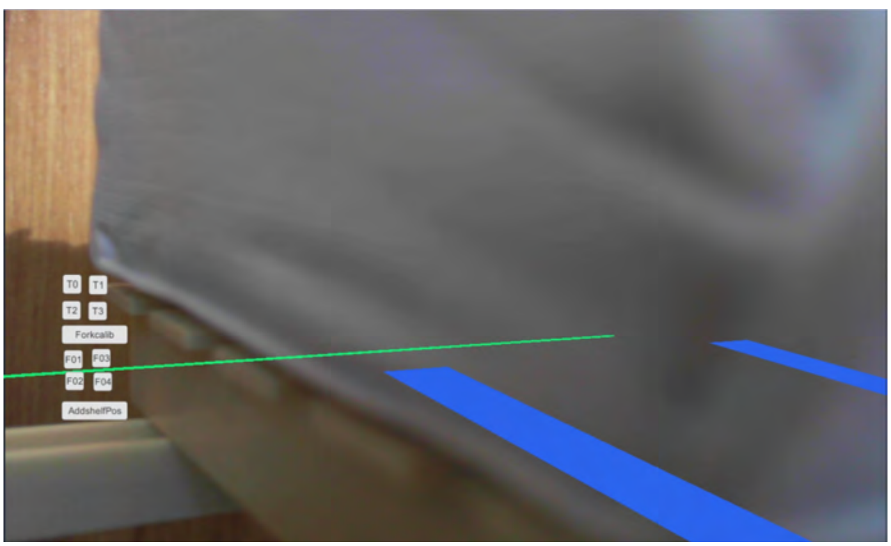


Figure 5.14: Green depth cue

line gives an estimate of how deep the fork can go to pick pallet up. The forks need not be aligned perfectly with the green line, a small error is fine as long as operator doesn't drift farther from the green line either side.

5.3.5 Pallet racking

This is the most difficult task of all since the major portion of camera view is blocked by the pallet on the fork. To achieve task with ease, we tried to devise a way similar to how the professional

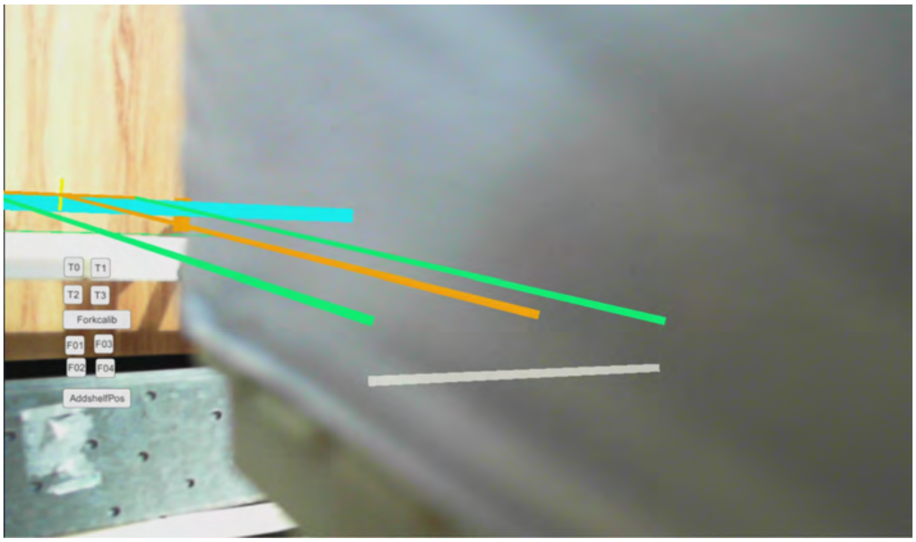


Figure 5.15: Pallet marker

forklift operator racks the pallet. The operator first lifts the pallet a little above the level of the shelf. Then, he/she slides the pallet inside and when he thinks the depth is enough, puts the pallet down. In this case, the pallet marker is augmented at a height a little above the level of the shelf. A white line is drawn below the level of the fork as a shadow of fork tips onto the shelf. The distance by which the pallet marker is moved up is approximately equal to the vertical distance between the horizontal forks line and the white line. Hence if the user lifts the pallet and aligns it to the pallet marker and slides the fork inside, the approximate orientation between the depth green line and white line is a good position to put the pallet down.

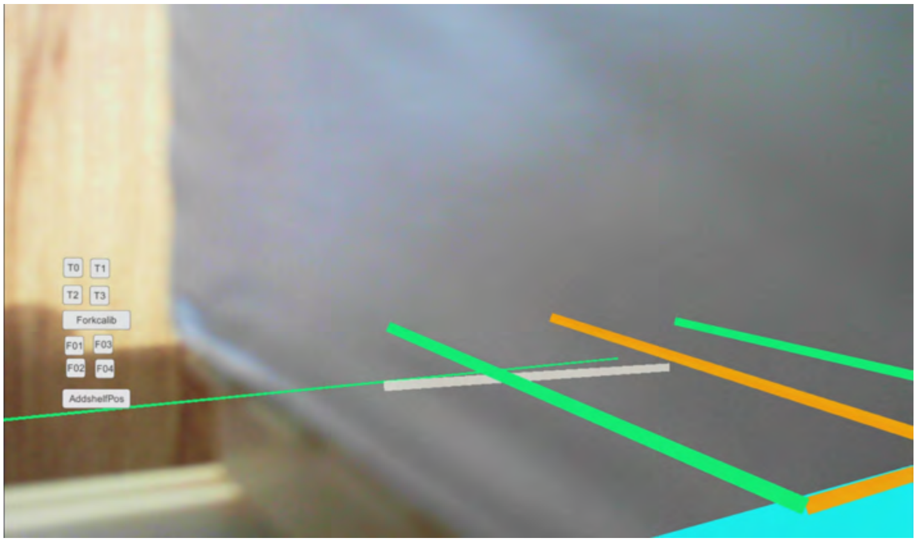


Figure 5.16: Aligning depth cue with white line

We can identify the white line drawn below the forks. The lines need not be exactly aligned and even if they shift either side a little, it is fine as long as the shift is not huge.

Chapter 6

Evaluation

This chapter explains the goals of the research study, the design of the study and evaluation of the results. After conducting the experiment, the process of evaluating the data and interpretation of the results is explained.

6.1 Study Design

To evaluate the use of the AR interface in pallet handling tasks for forklift operators, a user study was carried out which had three different tasks with two different conditions with and without AR visualization.

6.1.1 Hypothesis

The study consists of three simple tasks and so a total of three hypothesis will be analysed in this research.

$H_0$1- There is no significant difference between the performances of the participants using interfaces with-AR and without-AR cues while doing fork alignment.

$H_0$2- There is no significant difference between the performances of the participants using interfaces with-AR and without-AR cues while doing pallet picking.

$H_0 3$- There is no significant difference between the performances of the participants using interfaces with-AR and without-AR cues while doing pallet racking.

6.1.2 Environment

The experiment was set up in test space in the HIT Lab NZ. Four cameras were set-up to track the volume of the room where the tasks were carried out by the participants. The view of the forklift and the shelf was blocked to avoid the participant from looking at forklift instead of the interface. The participant was made to sit near the forklift since the remote operated on short range radio signals.

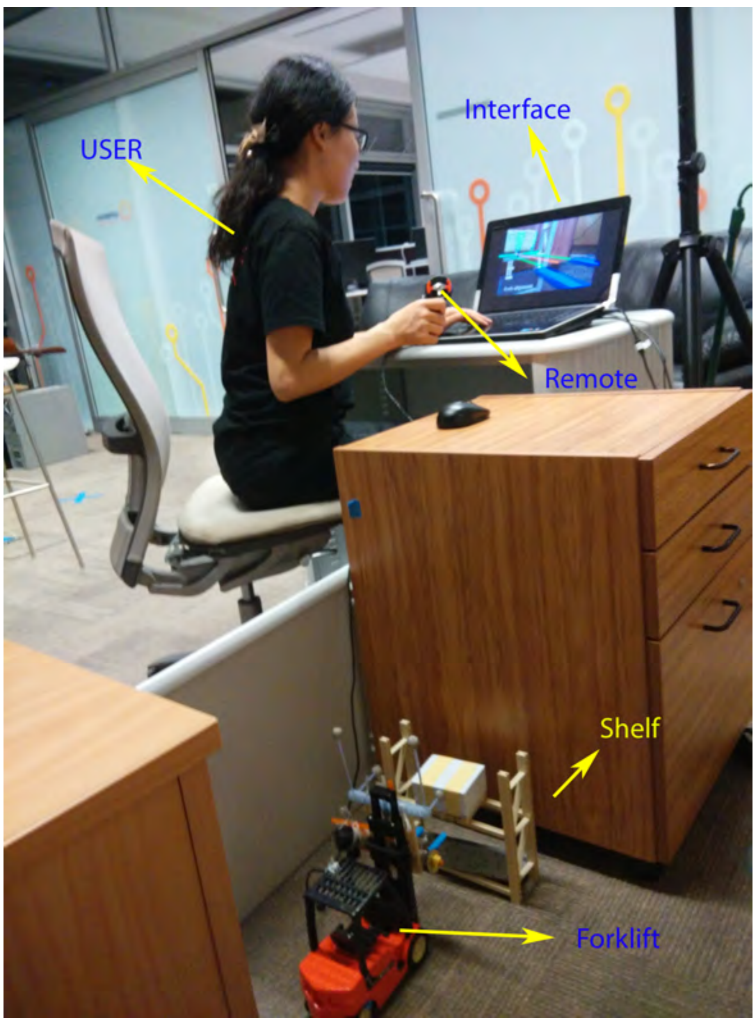


Figure 6.1: User Environment

6.1.3 Materials

- Toy forklift
- Motion tracking system (Four Flex-13 cameras + Opti-hub)
- Toy shelf and pallet
- laptop
- Two tables
- One chair

6.1.4 Measures

Pre-experiment questionnaire

Some demographic details were collected from the participants at the beginning of the experiment to give an idea about their experience with AR, video games and if they have any depth perception disorders.

System Usability Survey

The System Usability Survey (SUS) is a quick and reliable way to evaluate interfaces. It was created by John Brooke and consists of ten questions with five response option for the participants[1]. An additional seven questions were included in the questionnaire to study how participants felt about driving the toy forklift and if they felt any stress while doing the task.

Participant Performance Measures

The quantities measured while the participants were doing the experiment

[1] http://www.usability.gov/how-to-and-tools/methods/system-usability-scale.html

- **Task Completion Time**- For task-1, it is the time taken for the forklift to move forward and slide forks inside the pallet till the forklift moves back. For task-2, it's the time taken for the forklift to move forward and slide the forks inside the pallet until the participant thinks the depth of forks is enough to lift the pallets up. For task-3, it starts when the forklift moves forward until it places the pallet on the shelf.
- **Success or failure**- Success- If the task is completed without bumping the pallet down. Failure- If the pallet falls down from the shelf or into the shelf.
- **Bumps**- The number of times the forks bump with shelf or the pallet.

Questionnaire

At the end of experiment, participants were asked a few questions regarding the weakness and strengths of each condition and which interface they preferred the most.

The following notations will be used throughout the thesis evaluation

C1- Condition 1(Without AR cues)

C2- Condition 2(With AR cues)

Task-1- Fork Alignment

Task-2- Pallet picking

Task-3- Pallet Racking

T1C1- Task-1, Condition 1

T1C2- Task-1, Condition 2

T2C1- Task-2, Condition 1

T2C2- Task-2, Condition 2

T3C1- Task-3, Condition 1

T3C2- Task-3, Condition 2

ST1- Success rate in Task-1

ST2- Success rate in Task-2

ST3- Success rate in Task-3

BT1- Number of bumps in Task-1

BT2- Number of bumps in Task-2

BT3- Number of bumps in Task-3

6.1.5 Experimental Procedure

Participants were explained about the experiment and the components involved in it. They were asked to answer the pre-experiment questionnaire prior to the experiment. A small practice session was done for operating the toy forklift which include doing simple pallet handling tasks and moving the forklift around. Once the participants were familiar about the forklift and the controls, the view to the forklift is blocked to make sure that they look only at the interface while doing the experiment. The entire experiment is divided into three parts and each task has two conditions namely with and without AR depth cues. The participants were asked to repeat each task five times for each condition.

1. **Task-1-Fork Alignment**-The first task is designed to study how the operator aligns the fork with the pallet. The task is to move the forklift forward and align the forks with the pallet and then slide the forks inside the pallet and move the forklift back.

2. **Task-2-Pallet Picking**-The second task is to study how well the participants can judge the depth of the pallet. The forks are aligned prior by the researcher. The task for the participant is to move the forks inside and lift the pallet up and put the pallet down.

3. **Task-3-Pallet Racking**- The pallet is placed on the fork and the task of the participants is to move the forklift forward and place the pallet on the shelf.

At the end of every task, the participants were asked to fill the questionnaire which consisted of 17 Likert scale questionnaire and some descriptive questions.(See Appendix A)

6.1.6 Limitations

Although the toy forklift was easy to operate, the design of the remote controller was confusing. Even though they had ample practice before carrying out the experiment, some of the participants were confused. Most of the participants confused forward button to backward button. Hence when they aligned the forklift to the pallet or picked the pallet up, instead of moving backward, they moved forward resulting in bumping the pallet. The range of the signal is short and hence the position where the participant holds the remote also plays a role in effective operation of the toy.

6.2 Results

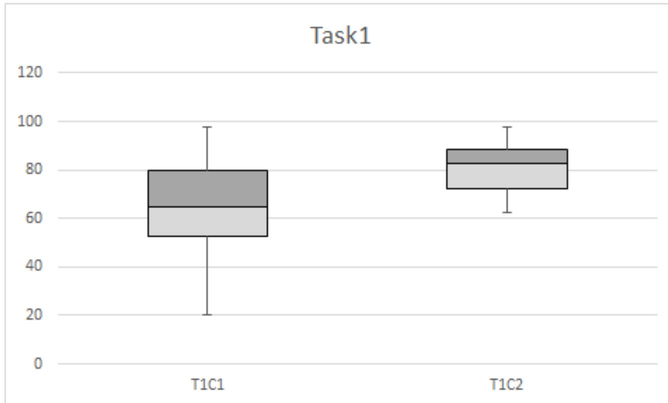
6.2.1 Demographics

Participants were recruited using posters advertised around the university and other relevant venues like Facebook. All of the participants were university students and out of 21 participants, 6 were female and 15 were male of age group ranging from 21 to 48 year old and average age of the participants was 28.7 years. Out of all participants, one participant had astigmatism which was rectified by lens.

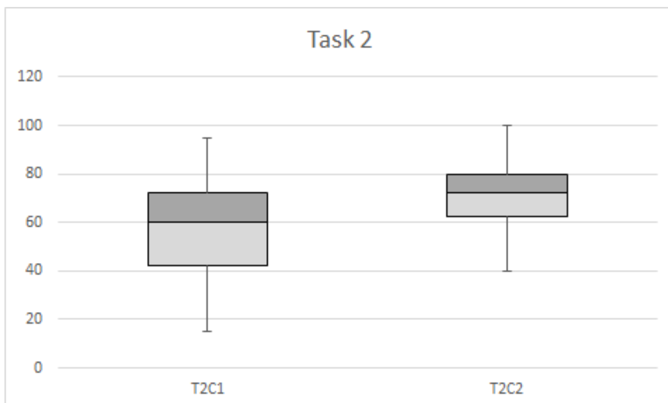
6.2.2 System Usability Scale

The perceived system usability of the two conditions in the three tasks was measured by system usability survey by all the participants.

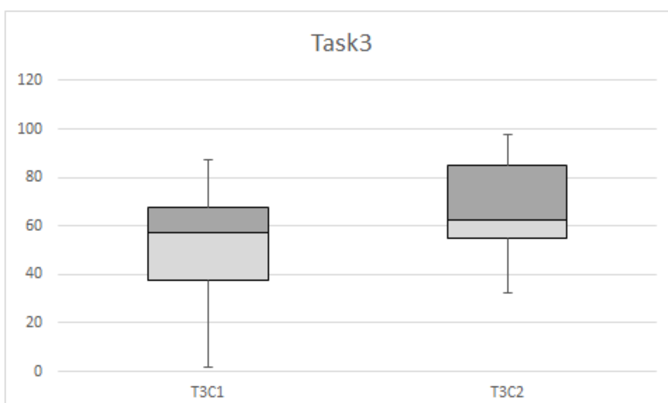
The conditions with the higher scores represent that the participants consider them better compared to the other conditions. The box plots drawn comparing the two conditions in each task shows that there is a significant difference between the interface usability with and without AR cues. The interface with the AR cues performed better than the other in all the three task cases.



SUS-Task1



SUS-Task2



SUS-Task3

Figure 6.2: SUS score for the three tasks

A Wilcoxon signed rank test was done on the feedback from each task with the significant level being set at $p < 0.05$ and it indicated that

- There is a significant difference found between the two conditions during the first task (*Z=-3.383,p=0.001*).
- There is a significant difference found between the two conditions during the second task (*Z=-2.703,p=0.007*)
- There is a significant difference found between the two conditions during the third task (*Z=2.703,p=0.042*)

Based on the feedback given by the participants, we infer that the interface with AR depth cues has higher usability score than the other interface.
Additional questions were asked to study additional information regarding the forklift operation and interface.

A Wilcoxon signed test was done on each question and the results are mentioned below.

Table 6.1: Wilcoxon Signed test

	Q11	Q12	Q13	Q14	Q15	Q16	Q17
Task-1	*Z=-2.887* *p =0.004*	*Z=-1.701* *p =0.089*	*Z=-2.556* *p=0.011*	*Z=-3.355* *p=0.011*	*Z=-2.2* *p=0.028*	*Z=-2.881* *p=0.004*	*Z=-2.835* *p=0.005*
Task-2	*Z=-1.469* *p=0.005*	*Z=-3.386* *p=0.001*	*Z=-1.961* *p=0.05*	*Z=-2.903* *p=0.004*	*Z=-0.92* *p=0.357*	*Z=-2.553* *p=0.011*	*Z=-2.823* *p=0.005*
Task-3	*Z=-1.851* *p=0.064*	*Z=-3.066* *p=0.002*	*Z=-2.138* *p=0.033*	*Z=-2.337* *0.019*	*Z=-0.867* *p=0.386*	*Z=-1.972* *p=0.049*	*Z=-2.171* *p=0.03*

Q11. I was performing the task well with the given interface.

For task-1, There was a statistically significant difference between the two conditions (*Z=-2.887,p=0.004*). For the second task, there was a statistically significant difference between the two conditions (*Z=-1.469,p=0.005*). There was no statistically significant difference between the two conditions in task-3 (*Z=-1.851,p=0.064*).

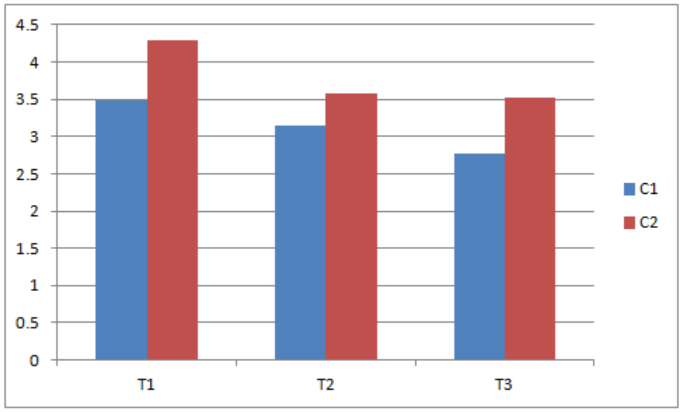


Figure 6.3: Q11-Mean comparisons

Q12. The given interface was useful to complete the task.

There was a statistically significant difference between the two condition in the first task (*Z=-1.701,p=0.089*). For task-2, there was a significant difference between the two conditions (*Z=-3.386,p=0.001*). There was a significant statistical difference between the two conditions in task-3 (*Z=-3.066,p=0.002)*).

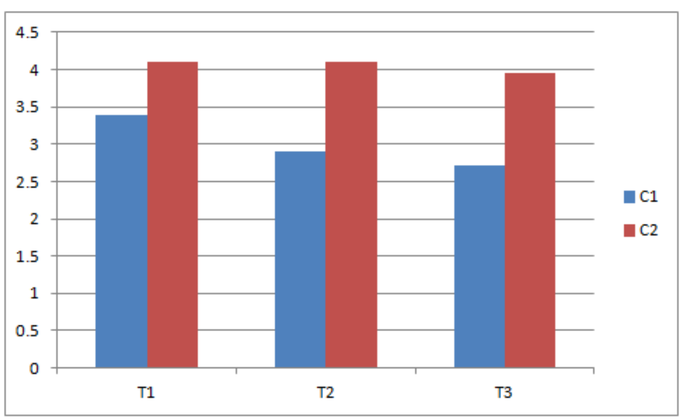


Figure 6.4: Q12-Mean comparisons

Q13-It was easy to operate the forklift

For task-1, there was a statistically significant difference between the two conditions (*Z=-2.556,p=0.011*). There was a significant difference between the conditions in task-2 (*Z=-1.961,p=0.05*) and task-3 (*Z=-2.138,p=0.033*).

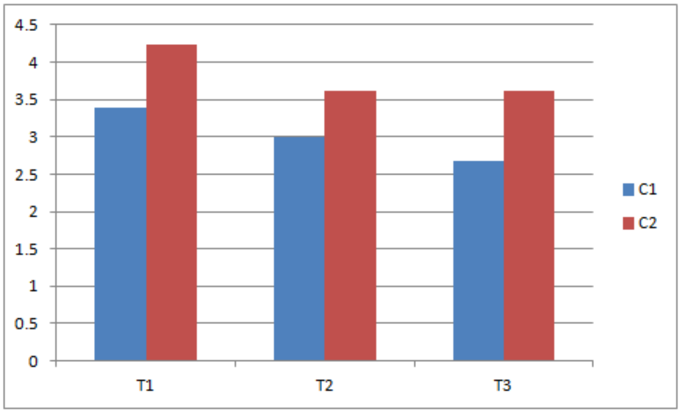


Figure 6.5: Q13-Mean comparisons

Q14-The interface was useful in helping me to operate the forklift properly

For task-1, there was a statistically significant difference between the two conditions (*Z=-3.355,p=0.011*). There was a statistically significant difference between the two conditions for task-2 (*Z=-2.903,p=0.05*) and task-3 (*Z=-2.337,p=0.019*).

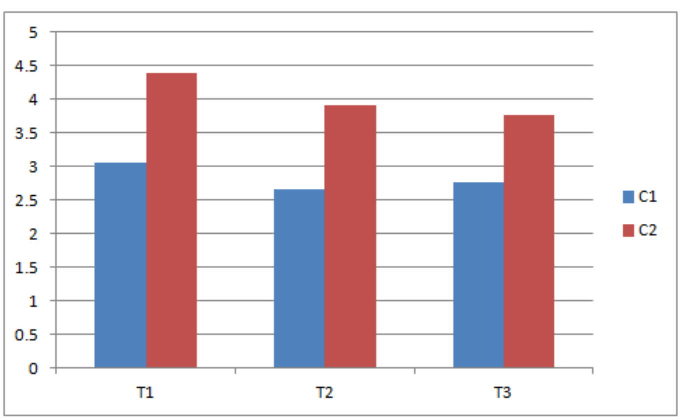


Figure 6.6: Q14-Mean comparisons

Q15-It was mentally stressful

There was a significant difference between the two conditions for task-1 (*Z=-2.2,p=0.028*). However there was no significant difference between the two conditions in task-2 (*Z=-0.92,p=0.357*) and task-3 (*Z=-0.867,p=0.386*) .

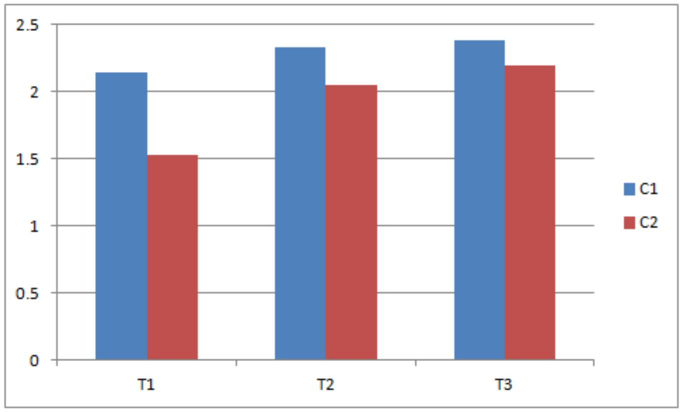


Figure 6.7: Q15-Mean comparisons

Q16-I would feel comfortable to use this on a regular basis while doing the tasks

There was a statistically significant difference between two conditions in task-1 (*Z=-2.881,p=0.004*). There was statistically significant difference between the two conditions in task-2 (*-2.553,p=0.011*) and task-3 (*Z=-1.972,p=0.049*).

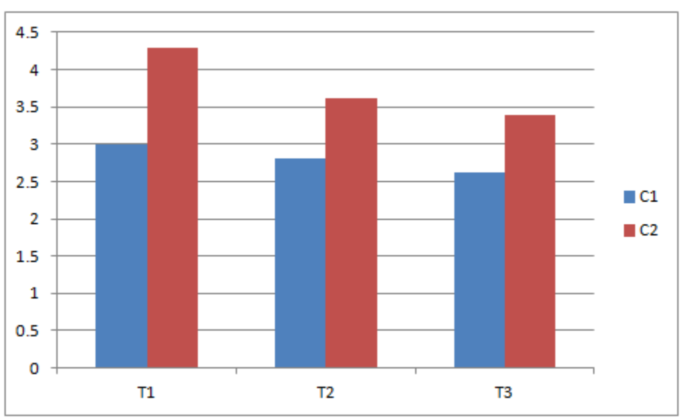


Figure 6.8: Q16-Mean comparisons

Q17-The overall experience was good

There was a statistically significant difference between two conditions in task-1

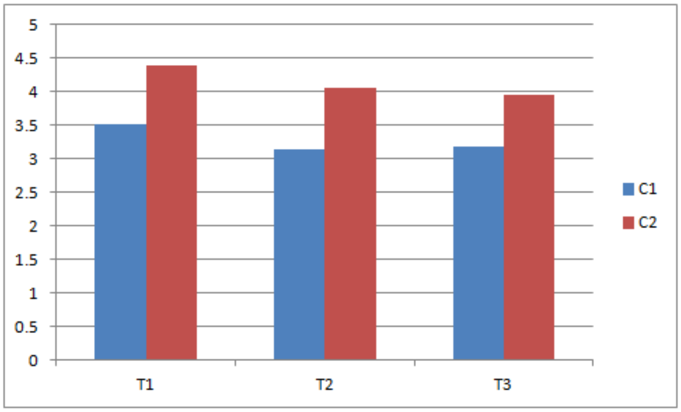


Figure 6.9: Q17-Mean comparisons

(*Z=-2.835,p=0.005*). There was statistically significant difference between the two conditions in task-2 (*-2.823,p=0.005*) and task-3 (*Z=-2.171,p=0.03*). As we observe from the table above, except in four cases (Q12 in Task-1, Q15 in Task-2, Q11 in Task-3, Q15 in Task-3), the other questionnaire shows statistically significant difference between the two conditions in three different tasks.

6.2.3 Performance Measures

The three measures we choose to study the performance of the participants are useful to study how well the given interfaces helped them in completing their tasks.

Task Completion Time

Task Completion time is the most important measure of the performance, since it is the main quantity which gives us an idea about how well the participants are completing the tasks.
The figure below depicts a comparison among the mean task completion times in the three task in two conditions.

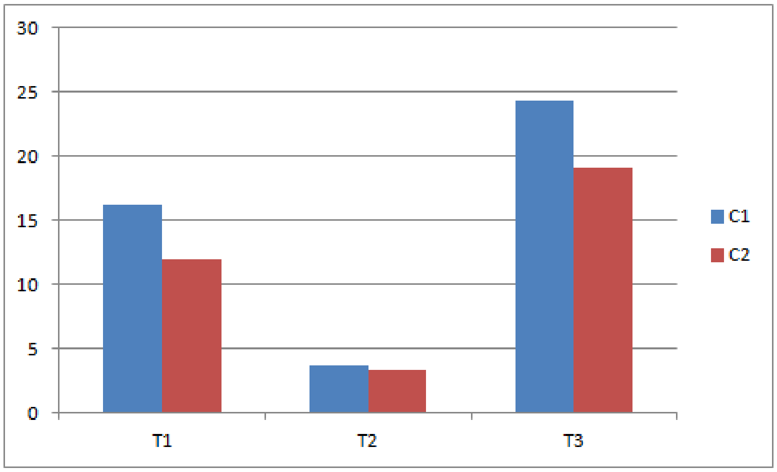


Figure 6.10: Task completion time- Mean

The figure below shows the box plots of the time for each tasks in both the conditions. The data

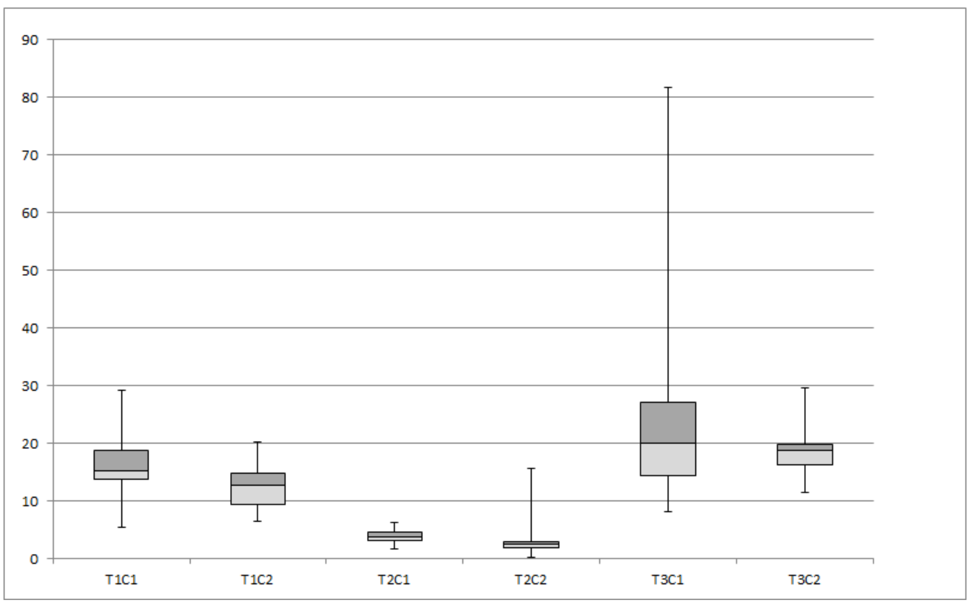


Figure 6.11: Task Completion time- Box plot

was further analysed by first checking it's normality. Since, time completion data of task-1 was normal, a paired t test was carried out on the data.

Table 6.2: Task completion for two conditions

Quantity	T1C1	T1C2	T2C1	T2C2	T3C1	T3C2
Mean	16.22	11.93	3.69	3.31	24.39	19.06
Median	15.3	12.82	3.53	2.6	21.5	18.42
Q1	13.8	9.48	2.92	1.84	15.75	15.92
Q3	18.77	14.08	4.55	3.03	28.62	20.13
SD	5.05	3.11	1.25	3.032	15.60	4.75
max	29.23	19.6	6.04	15.67	83.2	29.83
Min	5.5	6.5	1.53	1.46	9.6	11.2

There was a statistically significant difference between conditions 1 and 2 in the first task ($t(21)= 4.598$, $p<0.000$). Task completion time data for task-2 and task-3 were not normal and hence they were analysed using Wilcoxon signed test. The task completion times of both conditions in Task-2 are significantly different ($Z=-2.277, p=0.023$).However, there is no statistically significant difference between both conditions in task-3 ($Z=-1.477, p=0.14$). The inferences from Task-1 and Task-2 reject null hypothesis proving that the interface with depth AR cues is better than the interface without depth AR-cues. However there was no significant difference in time for task-3 hence accepting the null hypothesis that there is no significant difference between the two conditions.

Success Rate

The number of times participants completed their tasks without bumping the pallet is considered to measure the overall performance of the participants. The following figure compares the mean of success rate in both conditions in three tasks.

Shapiro-Wilk test was done on the data and verified that the data was not normally distributed. To further analyse the data, Wilcoxon signed test was used to verify if there is any significant difference in both the conditions.

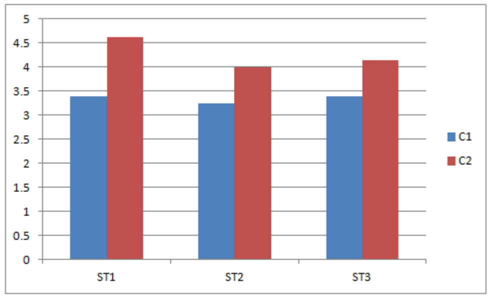


Figure 6.12: Success rate- Mean

There was a statistically significant difference between the success rate in task-1 between both conditions (*Z=-3.355,p=0.001*). The difference between the success rate in task-2 in both the conditions was statistically significant according to the test (*Z=-2.326,p=0.02*). For task-3, the success rate was proved significantly different (*Z=-2.113,p=0.035*). All the above inferences rejects the null hypothesis hence proving that there is a significant difference between both conditions.

Bumps

Number of bumps signifies how careful participants are while doing the tasks and how well they can judge the location of the fork. The figure below compares the mean bumps across all the three tasks in both conditions.

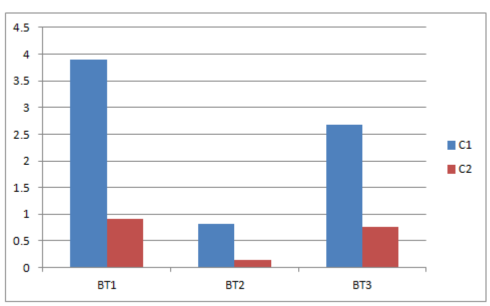


Figure 6.13: Bumps - Mean

The figure tells that there is significant reduction in number of bumps in tasks 1 and 3. Since in the task-3, the fork is aligned to the pallet prior to the task, the chances of bumping the pallet or the shelf is relatively lower and hence there is no significant bumps or difference in task-2. Shapiro-Wilk test was done on the data to find if it's normally distributed. The data was not normally distributed and hence further analysis is done using a Wilcoxon signed test to check if there is any significant statistical difference between the conditions for each task. For task-1, there is significant difference between both the conditions($Z=-3.726, p<0.000$). The difference between both the conditions in task-2 is significant with ($Z=-2.132, p=0.033$). Finally, There is statistically significant difference between the bump rate in task-3 with both the conditions ($Z=-2.936, p=0.003$).

6.3 Participants feedback

At the end of the experiment, participants were asked if they prefer the interface without AR cues or With AR cues and all of them preferred the interface with AR depth cues. There were asked about the weakness and strengths perceived by them for both the conditions. Some of them are listed below:

Without AR depth cues- Weaknesses

- Restricted view and in-accuracy.
- More chance of mistakes.
- Harder to use without experience.
- Accidents.
- Doubt and uncertainty.
- Stressful.

Without AR depth cues- Strengths

- Interface is simple.
- Less distractions.

With AR depth cues- Weaknesses

- Could be a little distracting.
- Blocks part of camera view.
- Little confusing with the lines.
- Concentration is split.

With AR depth cues- Strengths

- Accurate.
- More precise, easy to use once you get a hang of it.
- Better view of the target.
- Easier to understand the fork alignment.
- Simple.

6.3.1 Suggestions

- Most of the participants suggested that it would be good to have another camera which gives an additional view.
- Some of the participants felt that there are too many lines which lead to confusion.
- The lines partially block the real world and hence interface should have transparent lines.
- some participants suggested to remove some of the lines which they felt redundant.

Limitations

The main limitation while performing the experiment is the operation of forklift. Since it's a toy forklift, the movement wasn't very smooth and some participants were disappointed when they couldn't operate as desired. In task-2 and task-3, there was a depth cue showing where the fork can go, to pick the pallet or rack it. Since the forklift movement was not smooth they couldn't move the forklift as they wished to. The remote design was a little confusing causing operators to bump the pallet accidentally.

6.3.2 Observations by the researcher

1. Even though there was a thorough practice session to the participants, they found it difficult to operate the forklift, since the remote is little confusing and thus bumping the pallet even though they don't intend in doing that.

2. Since the experiment involves a toy, most of the participants were taking tasks as a challenge and even if the error is made due to inefficiency of the toy or disturbance in the signals, that was adversely affecting the feedback.

3. People with good judgemental skills tend to perform the task well even without the additional AR cues.

4. There were specific cases where the participant was doing well without the cues and when presented with a precise cues to use to move the forklift, they concentrated more on following the cues, ignored the natural cues provided by the camera feed and hence ended up making more errors than the previous case.

5. Some participants when presented with the interface with the cues, completed the tasks with just taking help from the cues ignoring the camera feed.

6. While doing pallet racking task with out the help of cues, the participants lifted the pallet up, navigated to the shelf and then placed it on the shelf by comparing the edge of the

pallet and the shelf. But in a real warehouse environment, a shelf has lots of racks and the the space allotted for a pallet is less. Hence, pallet racking cannot be done in the same way as in the experiment.

6.4 Discussion

Though we could partially recreate the environment forklift operators have, the toy forklift had its own limitations. Since we blocked the view of the forklift, the participants had to perform tasks based on the cues provided by the camera feed which is not the same in the case of real forklift. Since, it's a toy forklift, the movement is not quite smooth and when the participants were presented with precise cues like lines, they were stressed to navigate the forklift into that precise location resulting in more errors. Since the pallet is not loaded, it had the tendency of sliding away from the fork, which doesn't happen in the case of real forklift.

Some participants tend to perform extremely well even when there is a learning curve, but some participants were confused because of the lines. Even with all these limitations, all the participants preferred the interface with AR depth cues than the interface with just camera feed.

Chapter 7

Conclusion and Future work

This chapter explains the conclusions derived from the experiment, evaluation and the improvements that can be made in future work from the conclusions.

7.1 Conclusions

In this thesis we studied how Augmented Reality could be used to help forklift operators in warehouses, especially with pallet pick up and set down on warehouse shelves. The aim of this research was to develop a functional prototype which addresses the visibility issues of high reach forklifts. The final system included augmented depth cues for three main tasks namely fork alignment, pallet picking and racking. A robust system was implemented to perform a user study and evaluate the performance of the participants. Lot of observations and conclusions were derived and they are

7.1.1 Based on Interface

- Augmenting depth cues on the camera feed increases the performance and avoids mental stress and confusion to the operators.
- Operators have a choice of looking at both camera feed and the cues to perform their tasks.

- If the tracking information is accurate, AR cues are enough to perform the tasks.
- The virtual lines block some of the important information in the camera view.
- A combination of the depth cues and real world cues would benefit the forklift operator to the maximum extent.
- It was observed that some participants were mentally stressed by cues like lines, which needed forklift to move into precise location. Another study can be carried out to evaluate how the participants perform cues like lines and depth cues like grid lines where the user has to partially use their judgement.

7.1.2 Based on Participant's Performance

- Even though some operators performed well with interface with just the camera feed, prolonged use of the interface is stressful since they have to judge and observe many parameters like edges of the pallets, shelves and shadow to perform the tasks.
- If the controls of the forklift is smooth and precise, the participants would have done better in task-2, since they took lot of time aligning the forks to the line since the controls of the toy forklift weren't very intuitive.
- Some participants felt there are too many lines to follow.
- For the task of pallet racking, there was a learning curve but once participants understood how it works, their performance was good.
- There was a huge spike in the performance of the participants who showed less judgemental skills in the interface with just the camera feed.
- This interface will be best suited for the novice users with less experience in handling pallets.

7.2 Future Work

From the conclusions, here are some possible ideas to modify the interface for future work

- The lines in the interface can be made semi-transparent such that the lines don't entirely block the camera view.
- For the tasks involving depth cues, audio or visual feedback can be added to warn operators if they let forks go too deep.
- The number of lines can be minimized by just displaying the lines which are absolutely necessary.
- Lines in the interface can be made intuitive so that there is not much learning or confusion in the interface.

Many participants suggested that the view would be better if we had another camera fixed between the forks. Though that was one of the ideas, while doing the prototype which is to fix a camera between the forks, we couldn't include that in the experiment since we dealt with a toy. Making the system more redundant by only displaying the lines needed at particular distance would be useful for the users who get confused by the lines. An option to switch the lines off or on may increase the choice the operators have hence increasing the usability of the interface.
The immediate direction of this thesis is implementing the system on the real forklift in real warehouse set-up. Even though we conducted the user study on 21 participants, the experience was more like a game. Nothing serious was at stake unlike in the real warehouse set-up scenario. It would be comparatively little different to test the system using professional forklift operators who has experience in dealing with the issues. A pool of experienced and novice forklift operators can be choosen to conduct the user study such that the extent of help the interface gives to novice operators can be estimated. Unlike the simple tasks in this experiment, different tasks can be defined which includes all the three tasks to check the efficiency of the system.

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Chapter 8

Appendix

Information sheet

Research Study: Enhancing depth cues with AR visualization for forklift operation assistance in warehouse

Researchers: Bhuvaneswari Sarupuri, Christoph Bartneck, Gun Lee, Mark Billinghurst

Purpose: The purpose of the experiment is to see how well the AR visualization of the depth cues helps forklift operators in pallet handling.

Procedure:

The participant will follow the outlined procedure below:

1. The participant reads and signs the informed consent form.
2. Participant answers a questionnaire on demographic information and his/her experience with augmented reality, driving and toys.
3. Participant will be briefly explained about the experimental setup and tasks.
4. Participants will have practice of operating a toy forklift
5. The participant performs the following tasks in two conditions:
   - Uses the remote control to drive the toy forklift.
   - Watch a screen showing camera feed and other information while operating the forklift.
   - Operate the forklift and pick up a specific pallet from the aisle and place it on a specified shelf.
   - Answer a questionnaire asking of the usability of the interface used in the condition.
6. The participants answer a questionnaire about the overall experience and feedback.
7. The whole procedure will take approximately 40 minutes.

Risks/Discomforts:

The risks are minimal in this experiment. The participant operates a remote controlled toy forklift and drives as specified with the help of camera feed.

Confidentiality:

All data obtained from participants will be kept confidential. Results in aggregated format will be mainly reported in the thesis or publications and individual results will never be quoted. All recordings will be anonymized and confidential and only the researchers will have access to them. The data will be kept securely for a minimum period of 5 years and will be destroyed after completion of the research project.

Participation:

Participation in this research study is completely voluntary. You have the right to withdraw at anytime or refuse to participate entirely.

Compensation:

Participant will receive a gift voucher upon completion of the experiment.

Approval of This Study:

This study has been reviewed and approved by the Human Interface Technology(HIT Lab NZ) and the University of Canterbury Human Ethics Committee Low Risk Approval process.

Questions:

For any more details and queries, please contact the researchers

Bhuvaneswari Sarupuri (bhuvan.sarupuri@pg.canterbury.ac.nz)

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Gun Lee (gun.lee@canterbury.ac.nz)

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The University of Canterbury Human Ethics committee (human-ethics@canterbury.ac.nz)

Study of enhancing depth cues with AR visualization for forklift operation assistance in warehouse

CONSENT FORM

- I have been given a full explanation of this project and have had opportunity to ask questions.
- I understand what is required of me if I agree to take part of the research.
- I understand that participant is voluntary and I may withdraw at any information I have provided that this should remain practically achievable.
- I understand that any information or opinions I provide will be kept confidential to the researcher Bhuvaneswari Sarupuri and that any published or reported results will not identify participants.
- I understand that a thesis is a public document and will be available through the UC library.
- I have been informed of and understand the risks associated with taking part in this research study.
- I have been informed how these risks will be managed. These risks are not under the control of the researcher and they are eventually accidents or natural events. The experiment itself avoids any physical contact with researcher or objects within the facility in which the study is being carried out. I am only required to handle a remote control for the toy forklift.
- I understand that I am able to receive a report on the findings of the study by contacting the research at the conclusion of this study.
- I understand that I can contact the researcher Bhuvaneswari Sarupuri or her supervisors listed in the information sheet provided.
- If I have any complaints, I can contact the chair of the University of Canterbury Human Ethics committee trough the contact listed in the information sheet provided.
- By signing this document, I agree to participate in this research project.

______________________________ ___ /___ /2016

Signature of the Participant Date

Participant number#__________

Pre Experiment Questionnaire

1. Age ____
2. Gender (Male/Female)
3. Have you used any augmented reality applications before?
   - ☐ Not at all
   - ☐ Few times a year
   - ☐ Few times a month
   - ☐ Few times a week
   - ☐ Daily
4. Do you have a driving license?
   - ☐ No
   - ☐ Yes
5. Have you used any driving or parking assistance systems for driving a car before?
   - ☐ Not at all
   - ☐ Few times a year
   - ☐ Few times a month
   - ☐ Few times a week
   - ☐ Daily
6. Have you used remote or joystick to control toy vehicles or vehicles in video games?
   - ☐ Not at all
   - ☐ Few times a year
   - ☐ Few times a month
   - ☐ Few times a week
   - ☐ Daily
7. Do you have any depth perception or vision disorders that prevents you from driving?
   - ☐ No
   - ☐ Yes (if yes, specify)________________________________

HITLabNZ
Human Interface Technology Laboratory New Zealand
www.hitlabnz.org

Participant number#__________   *Condition-*

Questionnaire

1. **Rate the following based on how much you agree with the given statement**

Strongly disagree … Strongly agree

Statements	1	2	3	4	5
I think I would like to use this system frequently					
I found the system unnecessarily complex					
I thought the system was easy to use					
I think I would need the support of a technical person to be able to use this system					
I found that various functions in this system were well integrated					
I thought there was too much inconsistency in this system					
I would imagine that most people will learn to use this system very quickly					
I found the system very cumbersome to use					
I felt very confident using the system					
I needed to learn lot of things before I could get going with the system					
I was performing the task well with the given interface.					
The given interface was useful to complete the task.					
It was easy to operate the forklift					
The interface was useful in helping me to operate the forklift properly					
It was mentally stressful					
I would feel comfortable to use this on a regular basis while doing the tasks					
The overall experience was good					

2. **Please briefly explain, if anything made you feel hard, unnatural or stressful?**

3. **Any other suggestions to improve the interface?**

Participant number#__________

Post Experiment Questionnaire

1. What are the strengths of each condition?

Without Depth cue AR visualization	With Depth cue AR visualization

2. What are the weaknesses of each condition?

Without Depth cue AR visualization	With Depth cue AR visualization

3. Which interface do you prefer to use if you will have to perform a similar task again?
   - ☐ Without Depth Cue AR visualization
   - ☐ With Depth Cue AR visualization

   Briefly explain why you choose it

4. Any other comments or suggestions

Thank you!


See if you can drive forklift
Need Participants for a User Study in Human Computer Interaction.
You would be asked to:
• Operate toy forklift to perform simple pallet handling.
• Answer an anonymous relevant questionnaire.
40
min
Study Time - 40 minutes
Study reviewed by low risk HEC, UC
UC ENGINEERING
HITLabNZ
Human Interface Technology Laboratory New Zealand
For more details
bhuwan.sanupuri@pg.canterbury.ac.nz
To book a time
bhuwan.youcanbook.me