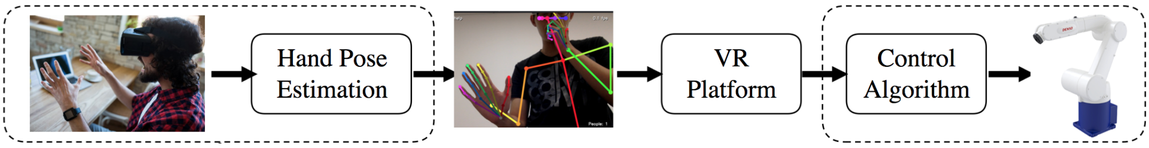
UM-SJTU Joint Institute

VE 450 Major Design Experience

Team 10 AR-Enabled Gesture Control of Robotic Arm I

Design Review #1



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Contents

1 Abstract

With the development of Industry 4.0 and advanced technologies, the concept of "smart factory" is established [1]. Our project, Augmented Reality (AR)-Enabled Gesture Control of Robotic Arm, aims to provide service of controlling of remote machines and providing a Virtual Reality (VR) preview platform. Our project can be divided into 3 stages in general: hand pose capture at the first stage of the client end, the VR platform and hand pose estimation at the second stage on server and finally robotic arm control at the factory end.

Karlsruhe Institute of Technology (KIT) Learning Factory features a learning system for helping students practice controlling machines under virtual environment. Digital Twin is another important concept of using VR to present and predict physical world. These two are the benchmarks and the intrinsic concept of this project.

We have 5 function requirements, which are accuracy of hand pose estimation in 62mPA, speed of pose estimation in 20FPS, accuracy of robotic arm in millimeter-scale discrepancy, delay between VR and hand pose estimation within 5ms, delay between VR and robotic arm within 5ms.

Our specified tasks are using OpenPose [8][9][10] by CMU to detect hand gestures, establishing VR environment and wireless communication (expected to be complete by Team 11), and finally we will use a PID control algorithm [11] and the WINCAPS [12] program to control the robotic arm. Notably we will be working collectively with Team 11 to complete the connections between different stages and platforms. We plan to finish those tasks one by one by the end of November.

2 Problem Description & Introduction

The concept of Industry 4.0 originated from an initiative launched by the German government in 2011 to promote the Digital Revolution in manufacturing [2]. One of the design goals of Industry 4.0 is to give better connection between people and machines [1]. Advanced human-machine interfaces, augmented reality devices and the use of trigger "real-time" training are all important components of Industry 4.0. The "smart factory" fostered by this concept involves the virtual copy of the physical world and real-time communication with humans [1]. With these advanced technologies – manufacturing of highly integrated products are on demand.

In general, our project aims to give a solution to remote control of machines in factories. To be more specific, our goal is to use different gestures to control the activities of the industrial robot to deliver designed functions, and the whole control process is visualized and demonstrated on a VR platform to help the online monitor. Therefore, this project can be divided into 3 stages.

The whole project is of a cascaded structure. The original data, hand gestures, go through the modules one by one and eventually reach the robotic arm in the factory. The robotic arm is expected to perform some limited gestures given by the hand, including moving, grasping, etc.

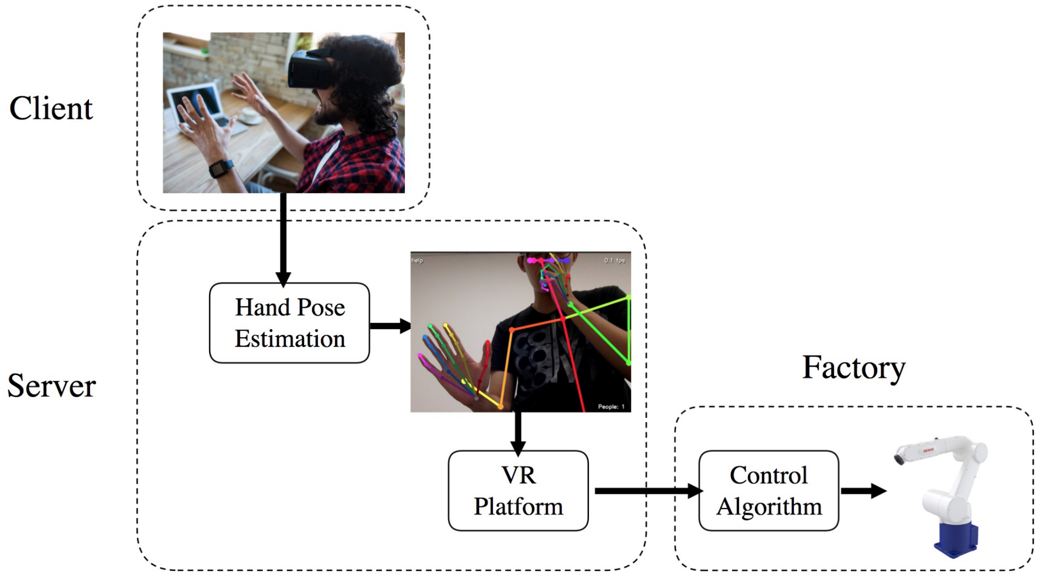


Figure 1: Overview of AR-Enabled Gesture Control of Robotic Arm.

2.1 Client End

The first stage is on the client end. A client can only use the camera on his or her laptop and do some gestures in front of it. The pose of the client's hand is captured by this monocular RGB camera. Then each captured frame is sent to a real-time hand pose estimation model. The output of this model positions the key points of the client's hand.

The hand pose estimation model is expected to be implemented by OpenPose [8][9][10] by Carnegie Mellon University, which is a robust but huge model for 2D face, body, and hand skeleton detection.

2.2 Server

The second stage is implemented on a server. As the hand pose estimation model is expected to be huge and complex, the computations will be run remotely. The VR platform will demonstrate the expected movements of the robotic arm and will also run on the same server. In the VR environment, the model of the robot arm will be that of the one in the factory. The virtual model will then have the same degrees of freedom as the real one. The solved spatial information of the client's hand joints is sent to VR platform at each frame. The position and the turning angle of each free joints of the robotic arm model is set according to the hand's spatial information.

As the robot's arm is mechanically different to that of a human hand, the spatial information of the hands will be further processed to fit into the robotic arm model. Since the hand pose estimation model and the VR platform is on the same server, we should link the two parts by setting the API between them.

2.3 Factory End

The final stage is the factory end, where the real robotic arm is located. All the movements of the real arm is synchronized with the virtual model.

The discrepancy between the virtual arm and the real one is expected to be at millimeter scale. To make the performance of the real one more stable, we apply some control algorithms like PID algorithm [11] to make some adjustment. Besides, since the factory can be far away from the server, we use wireless communication skill to transfer data from the server to the real arm.

3 Literature Review

This project is going to establish a system where users can use gestures remotely control a robotic arm and use VR platform to monitor. There are some benchmarks in the industry that are similar to our project, and these benchmarks are also the intrinsic concept of our project.

3.1 KIT Learning Factory

Karlsruhe Institute of Technology has developed a learning factory called Global Production [3]. Its target is to qualify industry leaders as well as students to be prepared for the changes of worldwide distributed factories. Different from other existing learning factories, which mainly focus on general concepts of production, the design concept of Global Production is to combine practice with theory. The developers of Global Production want to build a close-to-reality environment to help those involved practice and learn better.

In order to provide its users a close-to-reality environment, the Global Production learning factory applies several advanced technologies:

1. AI-augmented reality:

   In Global Production, AI-augmented reality is used to assist and guide users, it integrates the artificial intelligence image recognition algorithm into the learning factory. It will first show the users all the steps, then use an camera to observe the movement of users. As shown in Fig. 2a, by coloring the hands of users in its screen, the system will give users some feedback to show whether their operations are correct or not. Once one step is finished by users, the system will jump to next step.

2. Digital shop floor management:

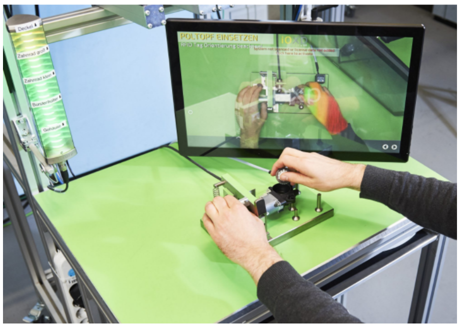
   The digital shop floor will record some key data or information from different user groups. Depending on the need, each user group will receive an adapted representation of the information or data they need, and then, deviations can be analyzed in the group and measures can be defined. Fig 2b is a concept map for this design.

3. Planium

   Planium is a control platform based on cloud technology. The planner of Global Production can plan the layout for the learning factory digitally in this platform and get some real-time feedback about the key performance indicators (KPIs). It also supports several planners to work together. To get a better understanding of the new layout, planners can directly view the new layout in a VR system from the cloud. Fig 2c is a concept map for this control platform.

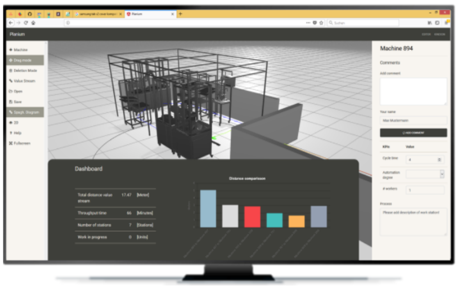
4. Robot Programming in Virtual Reality

   Global Production can program a lightweight robot for human-robot collaboration in a VR system. In order to create an environment in which the users can do some training like assembling or fixing the machine, Global Production will use sensors to identify the movements of the users' hands, then project them into the VR system. As shown in Fig. 2d, Global Production will display the relationship between users' hands and the machine in real time to help them practice. And to assist users in programming, some augmented reality elements are also displayed.

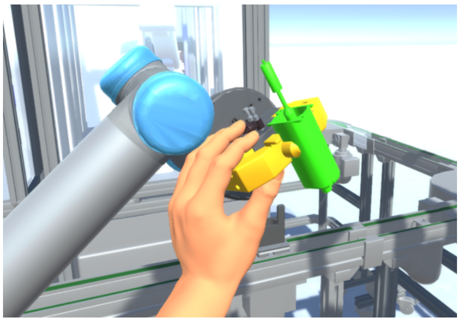


(a) AI-augmented reality

(b) Digital shop floor management



(c) Planium



(d) Robot Progamming in Virtual Reality

Figure 2: Global Production learning factory

Global Production is not only a learning factory, but also a blueprint for a possible new interaction between human and industrial production in the future industry 4.0 era [3].

3.2 Digital Twin

A digital twin is “a virtual representation of a physical product or process, used to understand and predict the physical counterpart’s performance characteristics.” [4]. The purpose of a digital twin in this project is to visually represent the robot arm in real time to the user. It is projected that by 2020, 30% of G2000 companies will be using data from digital twins to better optimize and improve their product innovations [5].

The digital twin will be operated using the camera on a user’s laptop which would capture the locations of their hands and gestures, thus controlling the twin. This twin's location and orientation in the VR space would then be transmitted to the actual arm to move in sequence. Data regarding the speed of the arm, errors, malfunctions and repeated movements of the user can be recorded for optimization and, in some cases, training of the actual robot arm. Creating a digital twin and uploading it on to a server for the end user to control allows several key benefits.

- Only one user can control the robot arm at a given time.
- Computing power is managed by the server – thus end user's requirements are minimal.
- Intuitive gestures allow learning to control the digital twin made easy.
- Data can be collected of user's gestures and movement to help troubleshoot errors.

3.2.1 Safety Standards

As the digital twin will be operated by a human user and thus control the physical arm; there are certain standards that must be met. As it is interacting with a human in a defined work space, we will take the standards for 'collaborative robots' [6]. To comply with American national standards [6], the system must provide a visual indication that the robot is in operation and one or more of the following requirements:

1. Safety-rated monitored stop.

· Robot must stop when operator arrives

· Robot motion responds to operator commands

· Non-collaborative operation resumes when operator leaves work space

2. Speed and separation monitoring.

· Robot speed correlates to distance between operator

· Stop condition if in contact with certain proximity.

3. Power and force limiting – by design or control.

· Robot reacts when contact is made

· Forces robot can exert are limited.

The digital twin in this project will follow the first requirement. As the control is based on the user's movement, in other words, operator's commands.

3.2.2 Case Study : Formula 1 Digital Twin

In a sport that is primarily based on beating the clock, efficiency is essential for companies involved. The McLaren group's tech subsidiary director Dr. Peter van Manen worked on what was their digital twin [7]. Essentially - a computer simulation of the actual vehicle that received 150 sensors measuring everything from the drive train to tire's quality. By collecting this data, small adjustments can be made to the driver and engineering teams to see where and when problems arrive.

What we can learn from their process is "Digital twins are not going to be perfect straight away" and will require a lot of testing and experiments before we "reap the benefits". Most digital twin's at the moment are kept very secret with little reports being released about them - as a result what we can take from the formula 1 model is that working closely with our user to robot model we should focus on capturing how a human would interpret a robot's movement using their hands. Building a digital twin is a slow and iterative process.

4 Customer Requirements and Engineering Specifications

4.1 Customer Requirements

Since we are going to provide customers with solutions to remote control of machines in the factory, our ultimate goal should be letting customers operate the remote machines in front of a laptop or an ordinary computer, as well as preview the whole process via a VR platform, as if they are in the factories, pushing the real button, grasping real things. The customer requirements can be specified as follows.

Real-time: To achieve more accurate control of the machines, the robotic arm should act in the factory right after the instructions are given by customers through their hand gestures.

Hand pose estimation: The robotic arm is not required to mimic every movement of hands. Only some basic gestures should be included like moving hands, grasping things, pushing the bottom, and etc.

VR model and VR environment: Since the VR platform serves as the visual demonstration and preview of what will happen in the factory, the VR environment should be set exactly the same as the real factory and the VR model of the robotic arm should be the exact copy of the real one. In this way, customers can adjust their gestures according to the VR demonstration, and know whether their operation is apt in the factory.

Synchronization with hand pose: The motion of the free joints of the virtual robotic arm model should be set according to the derived spatial information of the hands and the fingers of the customer. When a given gesture like grasping is detected, the virtual model should do grasping in the VR environment. The delay of this synchronization should be short.

Remote control: Since the machines might be at thousands of miles away from the customer, the instructions should be transferred through some wireless communication technology.

Synchronization with VR model: The real robotic arm should perform exactly the same as its virtual model on the VR platform does. The delay of this synchronization should be short.

4.2 Engineering Specifications

After analyzing customer requirement, we identified several engineering specifications as shown in the table below.

1	Accuracy of pose estimation in 62mPA
2	Speed of pose estimation in 20FPS
3	Accuracy of robotic arm in millimeter-scale discrepancy
4	Delay of communication between VR and hand pose estimation within 5ms
5	Delay of communication between VR and robotic arm within 5ms

Table 1: Specific Engineering Requirements

In order to build a real-time system, we want the delay of communication between VR platform and robotic arm and that between hand pose estimation system and VR platform to be as short as possible, and basing on current 4G wireless network speed, the delay can be controlled within 5ms. Also the hand pose estimation should be accurate and fast, according to current research in hand pose estimation field, an accuracy in 62mPA and images processing rate of 20 FPS would be reasonable.

For the hand pose estimation, since only some basic gestures should be included, we want it to be efficient, so its accuracy should be quite high and it should be able to process images fast.

Then for the VR model and environment, since this part is mainly handled by

Group11, the only thing we can do is to perform an accurate and fast hand pose estimation. Reducing the delay of communication can also be helpful.

And to synchronize the arm in VR platform with hand pose, the hand pose estimation should send continuous and accurate data to VR platform within short delay, so that some precise and consistent movements can be displayed in VR platform. Thus, the accuracy and rate of hand pose estimation is going to have a huge impact here, and short delay of communication is also needed.

The same, to synchronize robotic arm with the arm in VR platform, we should control the robotic arm with high accuracy, basing on the size of the robotic arm, the deviation should be controlled in millimeter-scale. Also, the delay of communication should be as short as possible, within 5ms should be enough.

Finally for remote control, in order to provide users with a good experience for the remote control, we want the communication to be fast and stable, thus the delay of the communication between different parts should be short enough, the same as the above, we believe within 5ms is enough.

4.3 Quality Function Development(QFD)

In order to meet all the customer requirements, we need several engineering specificatios, and as we have mentioned in last section, different engineering specifications is need for different requirements. To help us have a better understanding of the priority order of these engineering specifications, and the relationship between them, we made a QFD chart.

In the chart, we list all the customer requirements together with all the engineering specifications we have identified. Each row represents one customer requirement, and each column represent one engineering specification. And for different rows, we give different weights to different engineering specifications to show that how important this engineering specification is to achieving this requirement, 9 means the highest weight, and nothing means not important. For example, since we have mentioned that for hand pose estimation, its accuracy should be quite high and it should be able to process images fast, so for this requirement, we give the highest weight to accuracy of hand pose estimation and speed of hand pose estimation these two engineering specification, all the other specifications are not important for this requirement.

Also, we also set different weights to different customer requirements to reflect the attitude of customers towards different requirements. From 0 to 10, where 10 means the customers strongly emphasize this requirement, while 0 means the customers

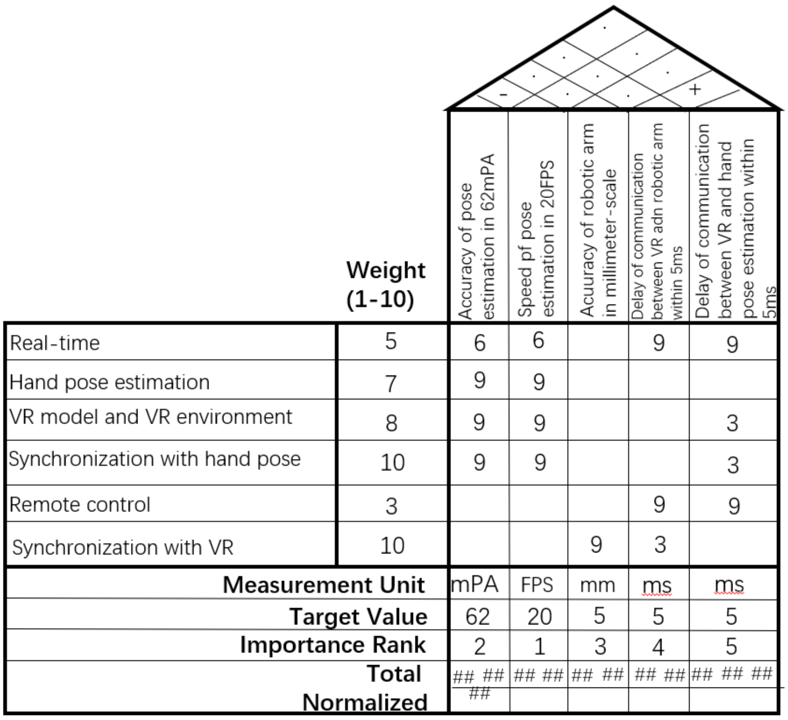


Figure 3: QFD chart

don't care about it. So in our project, the synchronization between hand pose estimation system, VR platform and robotic arm is the most important requirement according to our sponsor, while the real time requirement and remote control are relatively unimportant.

Thus, considering the weights of different customer requirements and the weights of different engineering specifications for different requirements, we get the importance rank for different specifications. We find the accuracy and speed of hand pose estimation are the most important specifications, then follows the accuracy of robotic arm, while the delays of communication are relatively unimportant.

By analyzing the relationship between different specifications, we find there is a negative relationship between accuracy and speed of hand pose estimation. High accuracy means more computational power is needed in hand pose estimation, which will slow its speed. Since we are only required to recognize some basic gestures in hand pose estimation, we give the speed of hand pose estimation a higher priority.

This QFD chart not only helps us to clarify the relationship between customer requirements and engineering specifications, but also help us to figure out the work we need to do and their priorities. With this QFD chart, we can make a reasonable and clear future plan for the whole project.

5 Project Plan

Our project is divided into five parts, Arm and hand pose detection & keypoints extraction, VR platform development, Wireless communication, Robotic arm installation& operations and Control algorithm. Our group is mainly charged of the first and the last two parts. Minhao Jin, Jingying Wang and Zhiyuan Xiang, these three ECE students are responsible for part 1; Nail and Wentao Yang, these two ME students are responsible for part 4; at last, all group members will work together for part 5.

5.1 Part1: Arm and hand pose detection & keypoints extraction

In this part, the first step is to do literature review of the related paper. Many works focusing on the body pose detection and extraction use convolutional pose machine which is condected by convolutional neural network. The second step is to find a good system that can extract arm and hand pose. Nowadays, there are many body pose extraction systems such as Alphapose, Maskrcnn and OpenPose [8][9][10]. Alphapose is delivered by SJTU, which has a good performance detecting people's skeleton, however, it cannot detect people's hand. Maskrcnn is conducted by Facebook, which can just detect the outline of the person and that is not what we want. OpenPose [8][9][10] is done by CMU, which is able to detect both people's hand and arm. It is robust enough, but needs much computation. When OpenPose [8][9][10] is in CPU mode, and is run in a laptop with CPU 2.7 GHz Intel Core i5 and the resolution of camera is 1080P, it can just reach 0.1Fps. However, when it is in GPU mode, and is run in a server with GPU 2080Ti, it can reach 12-30Fps. This step has been finished, and we have decided to use OpenPose [8][9][10] to implement arm and hand pose detection. The second step is to extract the keypoints of the arm and the hand. These are the two steps that have been finished.

The ongoing one is that we are now trying to use python and C++ API to extract the keypoints information. The final decision on using C++ or python is fully determined by Group11's need.

The final step in this part is to get 3D keypoints data and transfer to VR which is conducted by group 11.

At current stage, part 1 has the highest priority, cause only when we finish part 1, can we send data to Group11 and establish the interface.

The whole step is begun on September 30th, and planned to be finished on October 31st.

5.2 Part2: VR platform development

This part is going to build a VR platform to simulate and demonstrate the movement of the robotic arm. Group11 is responsible for this part.

5.3 Part3: Wireless communication

This part is going to build connections between hand pose detection system ,VR platform and robotic arm. Group11 is responsible for this part

5.4 Part4: Robotic arm installation & programming

The first three steps in this part is to learn some basic language based on the controller programming, use controller to control the robotic arm to grab items and read manual of the robotic arm. We have made a regulation on safety and figure.4 shows the details.

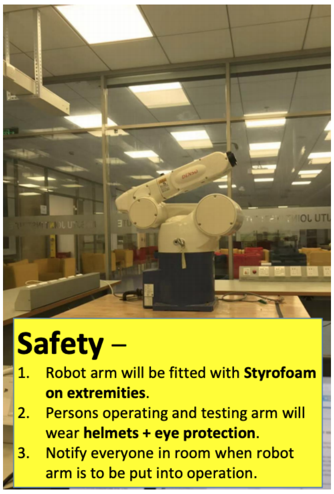


Figure 4: safety rule

These three steps have been finished and the ongoing two steps are programing in WINCAPS [12] to control robotic arm in PC and synchronizing between virtual environment and PC. The DENSO VM6083 can be operated in multiple ways. From our literature study of Denso's robot series, we found that using their WINCAPSIII [12] program will be the most suitable choice.

Our goal is to to take inputs from the VR space, implementing location and gesture of the hand in WINCAPS [12] and actively control the robot in real time relative to the user. The method we are trying to use is

1. Receive part locations and send estimate coordinates of hand to WINCAPS ¿ Move robot arm accordingly.
2. Implement gesture statements in WINCAPS [12], when signal is received robot 'hand' will open/close/rotate.

The whole part is started on October 13th, and planned to be finished on October 24th.

5.5 Part5: Control algorithm

This is out final step which means that we will finish the previous two steps and then begin to do this step. The algorithm now we want to implement is the PID algorithm [11]. PID algorhtim just has three parameters P, I, and D. P means a proportional term which is to close the feedback loop. I means integral term which is to assure zero error to constant reference and disturbance inputs. D means a derivative term which is to improve (or realize) stability and better dynamic response by performing "anticipatory" operation. The formula is as follows:

$$D_C(s) = K_P + \frac{k_I}{s} + k_D s$$

$$e_{ss} = \lim_{s\to 0} s \cdot \frac{1}{1 + G \cdot k_P + \frac{k_I}{s}}$$

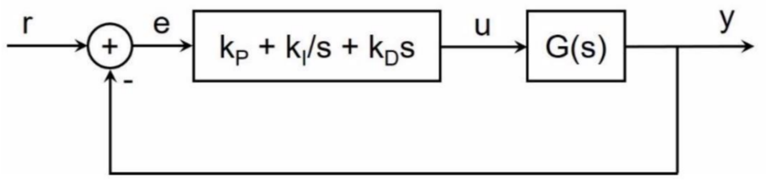


Figure 5: PID system

This step is planed to start on October 31st, and to be finished on November 25th.

5.6 Gantt Chart

This is the Gantt chart of our project plan.

And we set our first milestone on October 31st, by then, we should have finished Part1 and Part4. The second milestone is on November 25th, by then we should have finished Part5 and have our prototype. The final milestone is on December 9th, by then we should have been prepared for the expo.

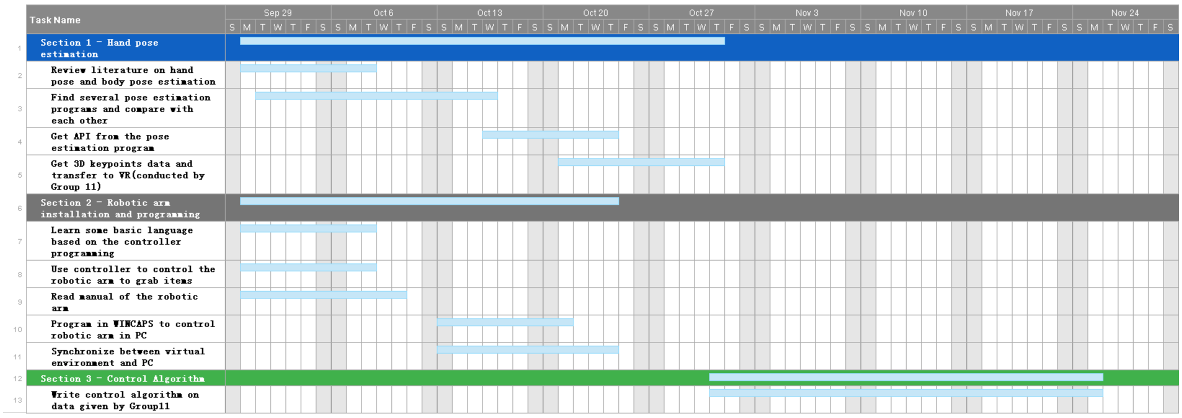


Figure 6: Gantt Chart

6 Conclusions

Our project, AR-Enabled Gesture Control of Robotic Arm is a totally new proposal in “smart factory”, but shares similarities with KIT learning factory and Digital Twin, which are the benchmarks. To meet the need of our target customers and provide better user experience, we decided on the engineering specifications on hand pose estimation, VR platform, and robotic arm control. Finally, we scheduled our tasks and this project is expected to be finished by the end of November.

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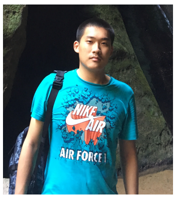
Bios

I am Jingying Wang, a senior student of UM-SJTU Joint Institute (JI) major in Electrical and Computer Engineering. In 2017, the first year of college, I worked as an trainee engineer at Nokia Shanghai Bell for one month, designing an integrated interface of code checking tools. In the second year of college, I won the Honorable Mention in 2018 Mathematical Contest in Modeling. In the same year, I joined System, Control, and Optimization Laboratory as a research assistant, developing a VR medical operation learning and practicing system. In 2019, I worked at Plug and Play China as operation intern and at JI as the teaching assistant of VE445 Intro to Machine Learning. I am interested and used to work in Image Assessment, Crowd Counting, Hand Pose Estimation, Action Quality Assessment, and Computer Graphics. My future career plan is to first pursue master degree and PhD degree and then work in industry. If possible, I will consider starting my own company.



My name is Zhiyuan Xiang, a senior student of UM-SJTU Joint Institute major in Electrical and Computer Engineering, I'm very interested in computer programming. In my sophomore year, I joined the VEX robotic team of SJTU, and won the second place in VEX national competition and second place in Asian Championships with my team. In the same year, I joined the Emerging Computing Technology Laboratory to do some research of approximate computing. In my junior year, I joined professor Yuan Bo's research group, did some research about the application of deep learning in high frequency trading. During the summer vacation, I went to Wenbo investment management Inc. for a one-month internship, I helped to build a market model for the company. Influenced by my personal experience, I'm extremly interested in computer science, especially for the artificial intelligence and machine learning, in the future, I plan to get a master degree first and then a PhD to further my study in this field.

My name is Minhao Jin, a senior student of UM-SJTU Joint Institute major in Electrical and Computer Engineering, I'm very interested in computer science and electrical and computer engineering. In 2018-2019, I worked in VEX robotic team. I'm mainly charged for wiring and programming and we win the championship in the campus competition, and the second prize in the national competition. In 2019, I began to work on indoor localization under Professor Han's supervision. I try to fuse channel state information and computer vision to increase the flexibility of camera and keep the localization accuracy as well. This is a very challenging work since there is not much work on it. I design a system and it is planned to publish on IEEE ICC 2020. Therefore, I really like this field.

My name is Wentao Yang, a senior student of UM-SJTU Joint Institute major in Mechanical Engineering. I like playing basketball, billiard, baseball and rugby. Besides, I like playing the piano. I like the sound of engine, the structure of gear matching with each other. In my freshman year, during the winter program holding by our institute, I went to Germany and learn more about Mechanical Engineering. In my junior year, I worked in Professor Hua Bao's laboratory about Solar Energy and worked with his graduate student publishing an essay in China. In my senior year, I took VM490 course of Professor David.Hung and began to learn about how to use Openfoam to simulate the fluid and watch the animation in Paraview. I really like the field of Mechanical Engineering, I believe whatever your idea is, only when you make it comes true, you have the hardware to run it or work on, then that makes sense. I plan to get my master and PhD degree abroad.

My name is Niall Halloran, currently on exchange for both fall and summer semesters for my senior year at UM-SJTU Joint Institute. At home, I study Mechanical Manufacturing engineering at Trinity college Dublin. This is my second design project – my first involved innovating for cyclists. My idea for vibrating handlebars for deaf cyclists achieved shortlist in two design competitions, 2019 Smarter travel campus awards and the Universal grand challenge; both based in Ireland. As a result – I really enjoy working with new ideas and emerging technologies. In the future I hope to work in a start-up or in an industry based around product innovation. Outside of engineering my interests include music, going to the gym and living a sustainable life.