Jenga Game App for Pick-and-Place 3D Printed Robotic Arm

Project Plan

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**List of Abbreviations**

3D Three-Dimensional
AR Augmented Reality
AI Artificial Intelligence
DOF Degree of Freedom
Game App Game Application
GUI Graphical User Interface
ML Machine Learning
1. Introduction

1.1. Background

The use and development of pick-and-place robotic arms can be traced to the mid-20th century, when George Devol invented the first programmable robotic arm in the world in 1954 [1]. In the early stages, robotic arms were designed to pick items from one designated position and place them in another designated position, through a predefined moving path. Unlike human beings, they were able to maintain high precision and efficiency without fatigue after working for long hours. Thus, they were widely adopted in the manufacturing industries and used to replace factory workers for performing repetitive assembly and installation tasks.

With the advent and advancement of artificial intelligence and computer vision, pick-and-place robotic arms are no longer limited to moving among various designated positions under predefined instructions. Instead, with microcontrollers and cameras installed, they are capable of deciding which items they should pick and where they should place within the reachable three-dimensional space. This has further widened the application of pick-and-place robotic arms. Playing pick-and-place games, which demands strategic thinking and precision control, is one of the areas that engineers want to apply robotic arms on.

1.2. Motivation

Jenga is one of the pick-and-place games which requires players to have strategic thinking and precise picking-and-placing skills. The standard Jenga tower contains 54 blocks and consists of 18 levels where each level has three blocks [2]. During the game, different players take turns to pick the movable blocks from the middle layers of the tower and place them on the top of the tower, until the game ends when the gradually unstable tower collapses [2].

As Jenga requires players to identify a loose block through trial and error, and carefully pick the blocks and place them on the tower, players need to have good hand-eye coordination in order to master the game. At the same time, in order to win the game, players need to come up with different strategies when picking the blocks so that when it is the opponent’s turn, the tower will become unstable and collapse during their picks. Jenga can thus act as a useful tool for players to perform cognitive training so as to improve their hand-eye coordination and skills in strategic planning. However, as the uncertainty and unpredictability of the opponents’ moves are the essential elements to make Jenga an exciting game, it is likely that people seldom play Jenga solely but treat it as a family and party game instead. Therefore, this project aims at building a robotic arm which can simulate as a real Jenga player to automatically test the blocks to see if they are loose, pick the selected block from the tower, and finally, carefully place it on the top of the tower. With this robotic arm, people can still play Jenga solely and use this game to train their cognitive skills even if they cannot find any companions to start the game.

In addition, before proceeding to the game, players need to manually build the Jenga tower first. This building process is usually not treated as part of the game as people may think that the playability of building the Jenga tower with blocks by hand is low. However, back in the olden days, when children did not have a variety of choices for entertainment, they would like to build Jenga towers or other different structures with toy blocks because they could create different scenarios with these structures, like a town with different skyscrapers and buildings, even though these scenarios might not be very authentic and realistic due to the identical colour and shape of the toy blocks and they could only imagine the scenarios and the whole picture virtually in their mind. Inspired by this observation, this project also aims...
to transform this structure building process into a fun game. By developing a Jenga Game App with different game modes and robotic arm controller function integrated, the players can try building the Jenga tower or different structures with the robotic arm instead of using their hands. AR technologies can also be used in the game to make the structure building game more interesting. This not only increases the playability of Jenga, which originally only has one game format, but also creates challenges for players since they have to control the robotic arm very well in order to place the blocks in the specific positions accurately. It can even act as vocational and industrial training for controlling machinery as in some industries, such as the construction industry and the logistics industry, workers are required to transport cargo or construction materials by cranes. Therefore, the Game App developed by this project can both be used for entertainment and for workers to train their skills of controlling the crane.

1.3. Related Works

1.3.1. Existing Jenga Game Applications

In the existing iOS and Android market, there are several game applications which can provide users with virtual Jenga gaming experience. Drag Towers Duel [3] features Jenga competition with virtual characters and the Jenga tower inside this application will simulate the shaking movement of a real physical Jenga tower after the users pick a virtual block from the tower. Balanced Tower AR [4] offers similar functionalities as the one provided in Drag Towers Duel, but it takes advantage of AR technologies, which allow users to put the virtual Jenga tower into real environment.

Although these virtual Jenga game applications adopt similar game rules and formats as the one used in the traditional physical Jenga, they make use of various game technologies and include a variety of virtual elements and storylines, and thus, create different variances of Jenga gaming experience, which are unique from the traditional physical Jenga for users. However, there still exist some fundamental differences in gaming experience between these two types of Jenga. In the traditional physical Jenga, whether the tower will collapse depends on various factors and the amount of force the players used can be a crucial factor to push or pull down the tower, while in those applications, since they are mainly built inside a virtual simulation environment and the movements and displacement of the virtual Jenga tower are calculated by the game physics engine, when the players pick the blocks by dragging on the screen, the physics engine will simulate the relative movements of the tower according to the change in position of the picked block. The amount of force the players use for dragging will not be taken into consideration during the calculation. Thus, players may sometimes find that the virtual Jenga will simulate some strange scenarios (see Figure 1) which will never happen in the traditional physical Jenga and the whole gaming experience will become less authentic and realistic for players.
1.3.2. Previous Robotic Jenga Research Projects

Using robotic arms to play Jenga is not a completely new concept in the engineering field. Researchers around the world have always been actively exploring and seeking out new methods to control the robotic arms such that they can automatically identify and extract the target block from the Jenga tower. MIT engineers [5] adapted an industry-standard robotic arm and customized it with a soft-pronged gripper, a force sensor and a camera, which can learn how to extract loose Jenga blocks precisely and efficiently by vision and touch through computer vision and tactile learning system. Wang, et al [2] developed a series of Jenga blocks extraction approaches, which can allow a five-DOF robotic arm controlled by a desktop computer to pick Jenga blocks from an unstable Jenga tower through analysing the position of the Jenga blocks and the structure stability of the Jenga tower.

Undoubtedly, the robotic arms created by researchers can achieve great success in mastering Jenga. However, most of these projects do not reveal their user interfaces for controlling the robotic arms. Some of them also make use of sophisticated sensors and components for building the robotic arm in order to push the limit of robotic arms and explore the possibility of applying robotic arms in Jenga. Thus, general users without professional knowledge can hardly know how they can control these robotic arms, or rebuild these robotic arms in order to put them into daily use.

1.4. Outline of this project plan

The remaining paper describes in more detail the goals that this project would like to achieve (section 2 - 4) and the technologies required for developing the proposed product (section 5). The game mechanisms and user interfaces used in the proposed product will also be discussed and illustrated (section 6 - 7), and finally, the logistics and management of this project will be suggested (section 8 - 9).

2. Objectives

This project proposes to develop a mobile Jenga Game App for a 3D printed pick-and-place robotic arm, which can enhance the traditional Jenga gaming experience of users by:
1) turning the robotic arm into a real Jenga player such that it can automatically pick loose blocks from the tower and place them on the top of the tower in order to allow users to play Jenga solely with the robotic arm and train their cognitive skills even if they cannot find any companions to start the game,
2) transforming the Jenga tower building process into a robotic arm controlling game so as to add variety to the traditional Jenga game,
3) developing user-friendly and easy-to-use graphical interfaces for users to proceed the game and control the pick-and-place robotic arm, and
4) exploring the possibility of applying AR technologies into the game application so as to integrate physical and virtual Jenga gaming experience in order to create different variances of Jenga which are unique from the traditional physical Jenga for users.

The following goals are set for this project and subject to change, depending on the progress of the project development.

1) The preliminary goal is to build a 3D printed robotic arm controlled by Arduino with Bluetooth module, which is capable of picking and placing Jenga blocks from one place to another. A robotic arm controller application will also be developed and delivered in the Android platform such that users can connect the application to the robotic arm via Bluetooth and control the movement of the robotic arm with control buttons inside the application.
2) The intermediate goal is to integrate an automatic pick-and-place function into the robotic arm controller application such that users can choose to allow the application to automatically communicate with the robotic arm and control the movement of the robotic arm to pick and place Jenga blocks from the Jenga tower without user intervention.
3) The ultimate/extra goal is to enrich the traditional Jenga gaming experience by integrating virtual contents into the robotic arm controller application with the use of AR. The project will also explore the possibility of providing users with a multiplayer gaming experience such that several users can install the same application in their own mobile devices and take turns to control the movement of the robotic arm with control buttons.

3. **Scope**

1) Android and iOS are two major mobile application platforms in the existing market. However, this project will only develop and deliver the game application in the Android platform since the development of Android applications is more flexible and more support can be found from the community due to its open-source nature.
2) This project is a pilot project exploring the possibility of using a low-cost and small-scale robotic arm controlled by a mobile application for playing Jenga. To reduce the difficulty level of the game, a 10-level Jenga tower will be used instead of the standard 18-level structure.
3) This project focuses on applying and utilising the existing available computer vision technologies and AI frameworks rather than inventing new algorithms in order to develop the product.
4) Jenga is an iconic and straightforward pick-and-place game compared to other pick-and-place games which require more complex pick-and-place movements. After mastering this game, the possibility of applying this robot into other more complex pick-and-place games can be explored.

4. **Advantages of the proposed product**
1) Low cost
The frames of the robotic arm used in this project can be printed by 3D printers while most of the sensing and computational work is performed by the built-in components of the mobile phone instead of using high-cost external sensors connected to the robotic arm. Therefore, the cost of developing this product is low.

2) Easy to use and setup
The Jenga game application has an intuitive graphical user interface so players do not need to have any prior knowledge before using the application. Also, users do not need to deal with the hardware components before using this product, which makes this product easy to use and setup.

3) High scalability
Each game mode of the Jenga game application in the proposed product is developed as a separate module. Therefore, in the future, more game modes in the form of modules can be added into the application to enhance its functionalities without affecting the main programs or other modules that are well tested and developed.

5. Project Prerequisites
5.1. Hardware

The hardware backbone of this project consists of an Arduino microcontroller board with a Bluetooth module, stepper motors, end-stop switches, a vacuum gripper, a 3D-printed robotic arm, a 3D-printed rotary platform and a 3D-printed static platform (see Figure 2).
- The Bluetooth module allows the Arduino microcontroller board to communicate with the mobile application through Bluetooth in order to receive instructions for moving the robotic arm.
- The end-stop switches help the robotic arm return to its home position.
- The vacuum gripper provides means for the robotic arm to pick and place Jenga blocks. Comparing with mechanical jaw grippers, vacuum grippers allow simpler controls for playing Jenga because two actions, i.e. pushing and pulling, are required to pick the middle block on each layer if mechanical jaw grippers are used, while only one action, i.e. sucking, is required to pick any blocks in the tower if vacuum grippers are used.
- The robotic arm used in this project is adapted from the one provided by HKU CS Maker-Lab [6], instead of designing and making a new robotic arm from scratch. It will be customized to suit the needs of this project.
- The rotary platform is used for changing the orientation of the blocks in the Jenga tower so that all of them can be reached by the robotic arm, while the static platform is used to hold the mobile phone in a fixed position.
- With the Jenga Game App installed, the mobile phone either acts as the controller for players to control the robotic arm manually, or acts as the eye and brain of the robotic arm to pick and place blocks automatically.

5.2. Software

5.2.1. Sketchup and Solidworks

While the robotic arm used in this project is adapted from HKU CS Maker-Lab, the design of this arm is not intended to be used for playing Jenga. Modification is needed for customising the robotic arm such that it can suit the needs of this project. Therefore, two 3D computer-aided design softwares are used for modifying the existing components and creating additional parts for the robotic arm. Since Sketchup can generate 3D parts with simpler operations but it is difficult to generate assemblies, it will be used for fast 3D modelling and prototyping. On the other hand, Solidworks can generate both parts and assemblies but more complicated operations are required so it will be mainly used for conducting motion analysis and rendering for visualisation so as to validate the design of the 3D models.

5.2.2. Arduino IDE and mBlock

Arduino programs should be installed on the Arduino microcontroller board so that it can receive controlling signals from the mobile game application and instruct the robotic arm to perform different actions. To do Arduino programming, mBlock, a block-based programming tool, will be used together with the official Arduino IDE due to its convenient function, which can convert graphical code blocks into text codes.

5.2.3. Android Studio

Since the Jenga Game App will only be delivered in the Android platform, Android Studio, the official Android development IDE will be used to design the graphical user interface and construct the software backbone for the application.

5.2.4. Vuforia AR engine and ARCore

In the later stage of development, this project will explore the possibility of integrating AR elements into the Jenga Game App. In order to create the AR content, Vuforia AR engine and ARCore will be used.
5.2.5. Google Colaboratory

Well-trained AI/ML Jenga blocks detection models, which take Jenga images as input and output the position information of all the candidate blocks for further analysis, are needed to empower the robotic arm with the ability of identifying potential loose blocks from the Jenga tower. Thus, Google Colaboratory will be used for the model training process due to its free-to-use but powerful GPU processing resources, which can reduce the time needed for training the detection model.

6. Approach and Methodology

In order to accomplish the aforementioned objectives and goals, the proposed product developed by this project consists of two major components, including the hardware, which is the robotic arm, and the software, which is the Jenga Game App.

6.1. Hardware - Robotic Arm

When customising the adapted HKU CS Maker-Lab robotic arm such that it can be used for playing Jenga, the following technical requirements have to be considered when modifying the structure of the robotic arm.

6.1.1. Degrees of Freedom

The robotic arm proposed in this project has four controllable degrees of freedom. Figure 3 shows how this robotic arm can move within the movable range along the four rotational axes.

![Figure 3 The movable range of the four-DOF robotic arm](image)

With these four degrees of freedom, the robotic arm is capable of reaching each individual block placed inside the Jenga tower, given that the Jenga tower is located inside the robotic arm’s reachable 3D space.

6.1.2. Forward and Inverse Kinematics
As one of the objectives for the proposed product is to automatically searching for the loose blocks and pick them from the tower, after the location of a loose block is identified and the corresponding coordinates are converted and calculated, the robotic arm needs to know how to move its actuators in order to reach the loose block based on the given location information. Forward and inverse kinematics are thus needed for achieving this task. Figure 4 shows the side view of the robotic arm and the corresponding x-y coordinate plane which can be used for forward and inverse kinematics analysis.

Figure 4 Robotic arm placing in the x-y coordinate plane

By using forward kinematics, with the joint angles ($\theta_1$ and $\theta_2$) and the length of the actuators ($l_1$ and $l_2$) given, the current position ($x_1$, $y_1$) of the vacuum gripper can be calculated as follow [7]:

$$x_1 = (l_1 \cos \theta_1) - (l_2 \cos \theta_2)$$

$$y_1 = (l_1 \sin \theta_1) + (l_2 \sin \theta_2)$$

After retrieving the current position ($x_1$, $y_1$) of the vacuum gripper, how the joint angle should be adjusted ($\theta_3$ and $\theta_4$) can then be calculated so that the robotic arm can move from the original position to the next targeted position ($x_2$, $y_2$) by inverse kinematics as follow [7]:

$$\theta_3 = \tan^{-1} \left( \frac{y_2}{x_2} \right) + \cos^{-1} \left( \frac{(l_1^2 + x_2^2 + y_2^2 - l_2^2)}{2 l_1 (x_2^2 + y_2^2)^{\frac{3}{2}}} \right)$$

$$\theta_4 = 360^\circ - \cos^{-1} \left( \frac{(l_1^2 + l_2^2 - x_2^2 - y_2^2)}{2 l_1 l_2} \right) - \theta_3$$

### 6.1.3. Suction required from the Vacuum Gripper

Vacuum gripper is the ‘finger’ of the proposed robotic arm, which provides suction force to pull the Jenga block out of the tower. If too less suction force is provided, the block can hardly be pulled out, while the whole tower can be pulled down if too much suction force is provided. Therefore, a sufficient amount of suction force has to be supplied by the vacuum gripper in order to pick the loose blocks from the Jenga tower. Figure 5 shows the equilibrium force distribution when the vacuum gripper is picking and holding the block, which can be used to calculate the suction force required to finish the pick.
Based on Figure 5, the suction force required can be calculated by using the following equations [8]:

\[
m_1 = \text{mass of each block} \\
g = \text{acceleration of gravity} \\
a = \text{acceleration when the vacuum gripper moves upwards with the block} \\
S = \text{safety factor} = 1.5 \text{ for vertical and horizontal movement} \\
\mu = \text{friction value} = 0.5 \text{ for wood} \\
F = \text{suction force required} = (m_1 / \mu) \times (g + a) \times S
\]

At the same time, the suction cup of the vacuum gripper also needs to provide a sufficient moment reaction to maintain the block in equilibrium. The moment required can be calculated by using the following equations:

\[
P = \text{pivot} \\
W_1 = \text{weight of each block} = m_1g \\
L_1 = \text{length between the center of gravity of the block and the pivot} \\
T = \text{moment required} = W_1L_1
\]

6.1.4. Torque required from the Servo Motor in the Wrist Arm

Servo motor in the wrist arm provides one of the four degrees of freedom for the robotic arm, which rotates the vacuum gripper in either vertical or horizontal direction. It also needs to supply sufficient torque reaction in order to support and maintain the vacuum gripper and the block being picked in horizontal direction. Figure 6 shows the equilibrium state when the servo motor can maintain the vacuum gripper and the block being picked in the horizontal direction, which can be used for analysing how much torque the servo motor has to output in order to maintain the equilibrium.
Based on Figure 6, the torque required can be calculated by using the following equations:

\[ m_1 = \text{mass of each block} \]
\[ m_2 = \text{mass of the vacuum gripper} \]
\[ g = \text{acceleration of gravity} \]
\[ P = \text{pivot} \]
\[ W_1 = \text{weight of each block} = m_1g \]
\[ W_2 = \text{weight of the vacuum gripper} = m_2g \]
\[ L_1 = \text{length between the center of gravity of the block and the pivot} \]
\[ L_2 = \text{length between the center of gravity of the vacuum gripper and the pivot} \]
\[ T = \text{torque required} = W_1L_1 + W_2L_2 \]

6.1.5. Hardware Control Signals and Communication by G-codes

The normal way to control the motion of a single stepper motor is by specifying the number of steps it needs to turn. However, to move the robotic arm, which consists of multiple stepper motors, from one point to another point, it is complicated to finish the movement purely by specifying the number of steps the motors need to turn. Thus, G-codes will be used in this project.

G-codes are the Geometric Code commands controlling the speed and moving path of the robotic arm for moving to a specific destination [9]. In this project, after the robotic arm receives the G-code commands from the game application, they will be interpreted by the public G-code libraries or self-defined interpreters to control the number of steps the motors need to turn in order to perform the required motion. Figure 7 shows an example of a G-code command.
From Figure 7, it can be seen that using G-code commands are simpler and more intuitive than specifying the step number of motors for controlling the movement of robotic arms in order to finish a simple motion, which is more convenient for developers to program the robotic arm to perform complicated motions.

6.2. Software - Jenga Game Application

The proposed Jenga Game Application includes three game modes, namely Creator Mode (tentative), Player VS Computer (CPU) Mode and Multiplayer Mode (tentative). The main menu of the application provides three access buttons for users to enter the three corresponding modes respectively (See Figure 8).
6.2.1. **Game Mode 1 - Creator Mode**

6.2.1.1. **Description**

Under Creator Mode, by using AR, players can get a taste of being a tower creator working in a virtual construction site. In this game, the player needs to build a Jenga tower according to the order from the boss (i.e. the order means the number of layers the player needs to build for the Jenga tower) by picking and placing the blocks with the use of the robot arm within a limited time period. The player will lose the game if he cannot finish within the time limit, while he can gain scores if the tower built by him matches with the requirements in the order.

6.2.1.2. **User Interface**

The following figure shows the graphical user interface after the user enters the Creator Mode.

![GUI Design of Creator Mode](image)

This game allows players to view the game scene from a first-person perspective. The background of the interface is the video live stream of the real environment taken from the phone camera. The application will create the AR virtual contents once it can find a flat plane in the real environment. In the upper part of the screen, players can see their scores, and the order from the boss which allows them to know the number of layers the player needs to build for the Jenga tower. In the middle part of the screen, players can see the AR contents created by the application, including:

a) The interactive virtual workers: They are implemented by Vuforia Virtual Buttons so that they can interact with physical Jenga blocks. When the player moves the physical blocks with the robotic arm, the blocks should not touch these virtual workers; otherwise, scores will be deducted.

b) The non-interactive virtual objects: They are used for decorative purposes.

In the bottom of the screen, buttons and a joystick are provided for players to control the robotic arm and the vacuum gripper.
6.2.1.3. **Workflow**

The following figure shows the overall workflow of Creator Mode.

![Workflow Diagram](image)

*Figure 10 Overall workflow of Creator Mode*

After the player enters Creator Mode, the application will scan for a flat plane to set up the AR environment while the robotic arm will restore to its home position. Then, the application will randomly generate an order for players to follow and build the required tower by using the robotic arm. During the building process, the application will continuously check if the robotic arm or the blocks hit the interactive virtual workers, and finally, it will check whether the tower built by the players meets the requirements stated in the order.

6.2.2. **Game Mode 2 - Player VS Computer Mode**

6.2.2.1. **Description**

Traditionally, people play Jenga with their families and friends as it is usually treated as a multiplayer game and it would be boring if the player plays Jenga alone without opponents. Under Player VS Computer Mode, the player may now opt for an interesting Jenga gaming experience by playing alone with the 3D Printed Robotic Arm. The robotic arm will simulate what a real person does while playing Jenga. It tests each wooden block to see if it is movable, picks the selected wooden block from the tower, and finally, carefully places it on the top of the tower.

6.2.2.2. **User Interface**

The following figure shows the graphical user interface after the user enters the Player VS Computer Mode.
The background of the user interface is the video live stream of the real environment taken from the phone camera. After the players finish their picks, they can press the START button and the robotic arm will automatically search for a movable block, pick it and place it on the top of the tower.

6.2.2.3. Workflow

The following figure shows the overall workflow of Player VS Computer Mode.
After the player enters Player VS Computer Mode, the robotic arm and the rotary platform will restore to their home positions. The player can start his pick first and then press the START button to let the robotic arm start its move. When the robotic arm is making its pick, the application needs to obtain both the front photo and the side photo of the Jenga tower in order to identify all the remaining blocks left in the tower. Thus, after the application obtains the front photo of the Jenga tower, the rotary platform needs to automatically rotate for 90 degrees to allow the application obtaining the side photo of the Jenga tower. After the robotic arm finishes its pick, the player will start his turn again and this cycle repeats until the tower collapses.

6.2.2.4. Strategies and Techniques

1) Pre-processing tower image for background removal
   Being the brain and eye of the robotic arm, the Jenga Game App takes photos of the Jenga tower by the built-in camera of the mobile phone, and then uses the Jenga tower photo as input to detect the location of each Jenga block by AI/ML detection models included inside the application. However, since the background noise of the Jenga tower photo may confuse the AI/ML models and affect the performance of Jenga block detection, the background of the photo needs to be removed. By using the Background Subtraction Method in OpenCV library, the background of the photo can easily be filtered and removed.

2) Identifying blocks location by object detection
   After taking the pre-processed Jenga images, object detection technology will be employed to identify the location of each individual block inside the image so that further checking analysis can be performed.
to determine which block is loose and movable. Thus, a dedicated Jenga block detector will be trained by using supervised learning. It takes the pre-processed images as input, and then outputs a set of bounding boxes, which describe the potential Jenga block regions, and the corresponding confidence score for each bounding box, which describes the probability of whether the regions drawn by the bounding boxes are the real Jenga blocks.

3) Studying block distribution by intensity analysis
After collecting the location information of each individual Jenga block, the distribution of the blocks in the tower and the center of force of the tower can be calculated. If the center of force of the tower is not located near the central axis of the tower, it can be reasonably deduced that the tower is tilting to the left if more blocks are located in the left part of the tower, or tilting to the right if more blocks are located in the right part of the tower. Thus, the tower is not a stable structure and a movable block near the tilting side should be picked to avoid the collapse of the tower.

4) Identifying loose blocks by brute force and elimination approach
To figure out all the possible loose blocks that can be removed without causing the collapse of the tower, all the theoretically possible block configurations in each layer of the Jenga tower is considered in Figure 13 [10].

![Figure 13 All the theoretically possible block configurations in each layer of the Jenga tower [10]](image)

Based on Figure 13, it can be observed that configuration (a) and (c) are practically impossible and the tower must collapse if any layer is in configuration (a) or (c) due to imbalance distribution of force and violation of fundamental laws of physics. Thus, the robotic arm only needs to determine whether it has to include the blocks from configuration (b), (d), (e), (f) and (g) as candidates.

In configuration (b), no blocks will be considered as candidates as there is only one block in this layer. The tower will immediately collapse if that block is picked.

In configuration (d), only the left block will be considered as one of the candidates as this configuration will become configuration (a) and the tower will immediately collapse if the middle block is picked. However, a lower priority will be given to this candidate because there is only one block left on this layer if this candidate is picked, which can easily cause the tower to collapse.

In configuration (e), no blocks will be considered as candidates as this configuration will become either configuration (a) or (c), and the tower will immediately collapse if any one of the blocks is picked.
In configuration (f), only the right block will be considered as one of the candidates as this configuration will become configuration (c) and the tower will immediately collapse if the middle block is picked. However, a lower priority will be given to this candidate because there is only one block left on this layer if this candidate is picked, which can easily cause the tower to collapse.

In configuration (g), all three blocks will be considered as the candidates. A higher priority will be given to these three candidates because there are still two blocks left on this layer if one of them is picked, which may not easily cause the tower to collapse.

The robotic arm can then try extracting each of the candidates according to the priority until one of the candidates can be pulled out without pulling down the whole tower.

5) Identifying the location and orientation of the top level of tower
According to Jenga rules, the picked block needs to be placed on the top of the tower in the direction which is perpendicular to the orientation of the upper layer blocks. Based on the detection result found in 2), the location and orientation of the top level of the tower can be identified and the robotic arm can thus put the block in the target position.

6.2.3.  Game Mode 3 - Multiplayer Mode

6.2.3.1.  Description

To increase the playability of the Jenga Game App, multiplayer mode is also included so that people can play the game together in parties and family gatherings. Under this mode, different players take turns to control the robot arms for picking blocks from the tower and placing them on the top of the tower. While the traditional Jenga game rules are still applied in this game mode, using robotic arm instead of hands to pick and place the wooden blocks creates challenges and a totally different gaming experience for players.

6.2.3.2.  User Interface

The following figure shows the graphical user interface after two users enter the Multiplayer Mode.
The background of the user interface is the video live stream of the real environment taken from the phone camera. There are also control buttons and a joystick provided in the user interface for players to control the robotic arm and the vacuum gripper. If it is the player’s turn, the control buttons and the joystick will be enabled and he needs to make his pick by using the robotic arm. Otherwise, the control buttons and the joystick will be disabled and the player will need to wait for his turn.

### 6.2.3.3. Workflow

The following figure shows the overall workflow of Multiplayer Mode when there are two players joining the game.
Assume there are two players joining the game in Multiplayer Mode. One of them will be the host while the other one will be the guest. The host will start the game first by connecting to the robotic arm via Bluetooth and make his pick while the guest will wait for his turn. After the host finishes his pick, the application will check if the tower collapses. If the tower does not collapse, the host will disconnect with the robotic arm and the guest will start his pick by connecting to the robotic arm via Bluetooth. This cycle repeats until the tower collapses.

7. **Risks, Challenges and Mitigation**

1) The tower may collapse when the rotary platform rotates
   In Player VS Computer Mode, after the application obtains the front photo of the Jenga tower, the rotary platform needs to automatically rotate for 90 degrees to allow the application obtaining the side photo of the Jenga tower. The potential risk is that the tower may collapse when the rotary platform is rotating. Therefore, the rotary platform should rotate slowly, gradually and steadily while sudden start and stop should not occur during the operation. In the worst case, the application should allow the users to take the two photos manually instead of taking the two photos automatically by rotating the Jenga tower.

2) The performance of the Jenga block detector is not ideal
   In Player VS Computer Mode, the location information provided by the Jenga block detector is crucial as the tower analysis and picking strategies are completely based on the detection result of the Jenga block detector. If the Jenga block detector cannot deliver accurate results (i.e. high false positive and false negative rates), the robotic arm can hardly know where it should pick and place the loose blocks. Therefore, when training the Jenga block detector, more Jenga images should be used as training data. The training data should also include the images of towers with different numbers of blocks and different arrangements of blocks in order to allow the Jenga block detector to learn sufficient knowledge in recognizing the features of the blocks. In the worst case, if the performance of the Jenga block detector is still not satisfactory, an alternative line and intersection detection model, which can identify the location of the blocks by reconstructing their contours based on the detected lines and intersections, should be used to replace the Jenga block detector.

8. **Project Management Information**

   8.1. **Software Development Practices**

   This project adopts an agile approach for the development of the proposed product. The implementation phase in this project will be further separated into different iterations. In each iteration, a workable prototype will be delivered based on what is done in the previous iteration, and at the same time, testing and evaluation of the prototype will be performed to suggest possible experiments and improvements for the next iteration.

   8.2. **Schedule and Milestones**

   Table 1 shows the schedule, milestones and the corresponding deliverables for this project.
<table>
<thead>
<tr>
<th>Phase</th>
<th>Period</th>
<th>Task</th>
<th>Deliverable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1 - Design &amp; Learning</td>
<td>Jul - Aug 2020</td>
<td>Research on project tools and the project topic</td>
<td>Proposal of the initial project idea</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Learn SolidWorks (basic 3D modelling, motion analysis for assembly, rendering for visualization) &amp; Vuforia engine (AR content implementation)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Draft the proposal of the initial project idea</td>
<td></td>
</tr>
<tr>
<td>Week 1 Sep 2020</td>
<td></td>
<td>Learn Android Studio (GUI design with Constraint Layout)</td>
<td></td>
</tr>
<tr>
<td>Week 2 Sep 2020</td>
<td></td>
<td>Learn Sketchup (fast 3D modelling and prototyping)</td>
<td></td>
</tr>
<tr>
<td>Week 3 Sep 2020</td>
<td></td>
<td>Draft the project plan</td>
<td></td>
</tr>
<tr>
<td>Week 4 Sep 2020</td>
<td></td>
<td>Develop the project webpage</td>
<td></td>
</tr>
<tr>
<td>Week 1 Oct 2020</td>
<td></td>
<td>Learn Android Studio (page transition and user interaction)</td>
<td>4 Oct 2020: Detailed project plan &amp; Project webpage</td>
</tr>
<tr>
<td>Week 2 Oct 2020</td>
<td></td>
<td>Learn Android Studio (Bluetooth communication) &amp; Arduino Programming</td>
<td></td>
</tr>
<tr>
<td>Iteration 1</td>
<td>Week 3 Oct 2020</td>
<td>GUI Design of the Game App</td>
<td>Workable robotic arm controller app (Half of Game Mode 1 completed)</td>
</tr>
<tr>
<td></td>
<td>Week 4 Oct 2020</td>
<td>Build the robotic arm with vacuum gripper</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 1 Nov 2020</td>
<td>Implement the controller function of Game App</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 2 Nov 2020</td>
<td>Testing &amp; debugging for the controller function of Game App</td>
<td>Workable robotic arm controller app (Half of Game Mode 1 completed)</td>
</tr>
<tr>
<td></td>
<td>Week 3 Nov 2020</td>
<td>Train the Jenga block detector</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 4 Nov 2020</td>
<td>Configure automatic pick-and-place procedures of robotic arm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 1 Dec 2020</td>
<td>Revision period</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 2 Dec 2020</td>
<td>Assessment Period</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 3 Dec 2020</td>
<td>Integrate automatic pick-and-place function into controller app</td>
<td></td>
</tr>
<tr>
<td>Phase 2 - Implementation</td>
<td>Week 4 Dec 2020</td>
<td>Testing &amp; debugging for the automatic pick and place function</td>
<td>Workable Jenga Game App (Game Mode 1 completed) (Game Mode 2 completed)</td>
</tr>
<tr>
<td>Iteration 2</td>
<td>Week 1 Jan 2021</td>
<td>Preparation for the first presentation</td>
<td></td>
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<tr>
<td></td>
<td>Week 2 Jan 2021</td>
<td>First presentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 3 Jan 2021</td>
<td>Draft the interim report (Part 1)</td>
<td>24 Jan 2021: Preliminary implementation &amp; Detailed interim report</td>
</tr>
<tr>
<td></td>
<td>Week 4 Jan 2021</td>
<td>Draft the interim report (Part 2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 1 Feb 2021</td>
<td>Create AR contents for Creator Mode</td>
<td>Workable Jenga Game App (Game Mode 1 completed) (Game Mode 2 completed)</td>
</tr>
<tr>
<td></td>
<td>Week 2 Feb 2021</td>
<td>Integrate the AR contents into the Game App</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 3 Feb 2021</td>
<td>Testing &amp; Debugging for the AR implementation</td>
<td></td>
</tr>
<tr>
<td>Iteration 3</td>
<td>Week 4 Feb 2021</td>
<td>One-month buffer for overruns / Explore the possibility of implementing Game Mode 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 1 Mar 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 2 Mar 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 3 Mar 2021</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 4 Mar 2021</td>
<td>Overall Testing &amp; Debugging for the Game App</td>
<td>Workable Jenga Game App (Game Mode 1 completed) (Game Mode 2 completed) (Game Mode 3 completed if possible)</td>
</tr>
<tr>
<td>Iteration 4</td>
<td>Week 1 Apr 2021</td>
<td>Draft the final report (part 1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 2 Apr 2021</td>
<td>Draft the final report (part 2)</td>
<td>18 Apr 2021: Finalized tested implementation &amp; Final report</td>
</tr>
<tr>
<td></td>
<td>Week 3 Apr 2021</td>
<td>Final presentation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 4 Apr 2021</td>
<td>Design project poster &amp; Create a 3-min project video</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Week 1 May 2021</td>
<td>Project exhibition</td>
<td>Project poster &amp; 3-min project video</td>
</tr>
</tbody>
</table>

Table 1 Schedule, milestones and the corresponding deliverables for this project
9. **Budget**

Table 2 shows the budget requested for this project.

<table>
<thead>
<tr>
<th>Item</th>
<th>Budget requested</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic components for the robotic arm</td>
<td>HK$700</td>
</tr>
<tr>
<td>(vacuum gripper, stepper motor, servo motor)</td>
<td></td>
</tr>
<tr>
<td>3D printing materials (ABS plastic)</td>
<td>HK$300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>HK$1000</strong></td>
</tr>
</tbody>
</table>

Table 2 Budget requested for this project

10. **Conclusion**

With the advancement of AI technologies, the robotic arm can be further put into wider use, especially in games and entertainment. In this pilot project, the possibility of playing Jenga with a 3D printed robotic arm by using a dedicated Jenga game application will be explored. This paper can serve as a development plan outlining how the proposed product can be implemented and how the aforementioned objectives can be achieved. While there may be risks which can potentially affect the development of the proposed product, several alternative approaches are proposed to minimize their negative effects, and finally, the traditional gaming experience of Jenga can hopefully be enhanced through this project.

11. **References**


