AceMaster: Tennis Training Robot
Final Report

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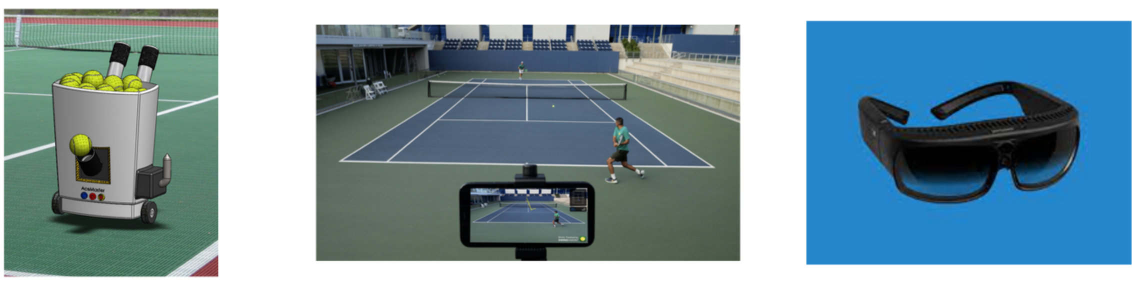
1 Product Description and Background

1.1 Description

AceMaster is an innovative robotic training system designed to assist tennis players in improving their skills via advanced computer vision technology and real-time feedback. The system combines precision tracking, artificial intelligence, traditional ball machines and Augmented Reality to offer personalized, data-driven and fun coaching experiences for players of all levels.

The way it works is simple: A tennis robot, similar to a tennis ball machine, shoots the ball at the user, with varying movement speeds and ball trajectories. Once the user has hit a few rounds, (a minimum of 2) cameras pick up the user's gestures using Computer vision technology, recording movements and gestures. It analyzes this data in real-time and compares it to a database of tennis faults (service, foot, double, etc) stored in the cloud. In the case of a fault, suggestions and tutorials are displayed on the AR glasses, as well as other match training information. Additionally, the robot changes ball parameters until the user masters certain tennis techniques. Finally, the players can provide feedback on the effectiveness of the instructions to help the Machine Learning improve.



Ball Robot   Camera Vision System   AR Glasses

Figure 1: Main components of the system

1.2 Background

Traditional tennis coaching is limited by factors such as availability, cost, and consistency. AceMaster addresses these limitations by providing 24/7 availability, cost efficiency through shared use, and consistent, data-driven feedback. The system aims to enhance players' skills, develop muscle memory, and prevent injuries by ensuring correct techniques through continuous monitoring and analysis. This would initially be sold to other businesses such as gyms or private clubs as a supplement to a tennis coach, until there is enough development of Machine Learning, and confidence in the private market.

2 System Level Design Requirements

Requirements for this product are a translation of customer needs, mainly based from a business and technical standpoint. Examples of business needs would be that the product has a longer lifetime than the Break-Even-Point, it's safe to operate without supervision, and most importantly, it offers similar training benefits as a tennis coach. Meanwhile technical needs would be variable force and ball trajectories from the system, reasonable safety measures, and minimum assembly.

2.1 Functional

- The robot needs to oscillate 180 degrees vertically and horizontally to cover all possible ball trajectories of a real player.
- The system must recognize at least 25 body key points from the users and adjust robot parameters such as ball force and trajectory accordingly.
- The system must recognize technique issues from the player, including serve, footing, back-hand, front-hand and slice with larger than 95% accuracy.
- The system must correct the users' technique issues with the same instruction as an average coach. This can include showing the user tutorial videos on different techniques.
- The robot must have a max serving speed of 200km/h, the average of a professional player [1].

2.2 Performance

- The robot, camera systems, and AR glasses should have an average running time of 90 minutes, the average for a best-of-3 tennis match [2], which requires sufficient battery life for each component and the function to collect balls from the ground.
- The camera vision system needs to outline the boundaries of the court with an accuracy of about +/-3.5cm, the same as the radius of a tennis ball [3].

2.3 Constraints

- The robot must not be taller than 188cm, the average height of the top ten male tennis players. [4].
- Wicked problem: the extent of the issues with machine learning and gesture recognition can only be understood while the system is being developed.

2.4 Interface

- The controls for the robot shall be controllable from the AR glasses.
- There shall be physical buttons on the robot for a basic setup (testing ball shoot, on/off, emergency stop, etc).
- Additional controls for the camera shall be done on a smartphone app for video recording and social media integration.

2.5 Reliability

- Any moving part in the robot should be easily accessible in the case of repair, maintenance, or jam.
- Wireless communications between the robot, camera, and AR glasses shall be robust (not hindered by radio interference, blocked by trees, etc).

2.6 Safety

- The system must have physical and virtual emergency stop buttons on the robot and AR glasses in case of robot malfunction or player injury.
- The camera systems must have a fail-safe feature to recognize if the player has stopped moving, to stop the robot and prompt a "Are you still there?" message.

2.7 Legal and Environmental

- The system must follow FCC 15 laws relating to electromagnetic interference for the electronic components.
- The system shall offer support for smartphone cameras as part of the vision system to cut down costs and environmental waste.
- All battery-powered electronic components shall have removable batteries for safe recycling.
- The system shall use as many off-the-shelf parts as possible to reduce waste and incentivize repairs.

3 System Architecture

The proposed system architecture consists of three main modular components: The tennis robot, the camera vision system, and the AR glasses. The idea is that you can add more cameras and robots to suit more users, or emulate real tennis matches. In the figure below one can see the graphical representation of the system requirements, with logical flows of information from one functional component to the other.

4 Concept Generation

Now that it's known what to expect from the system and it's architecture, the same can be applied to the concepts we generate. To do that, we'll explore the elements of concept architecting, so known problems can be tested for before the modelling and prototyping phase.

1. **Robustness:**
    - The system is adaptable to various lighting conditions and player skill levels.
    - There are non-linear behaviours at the robot boundary conditions: the robot's moving parts degrade faster than the camera or AR glasses; the system has issues like partial fractures and loose screws.
    - Offering calibration tests for all components can tell the user how each component is degrading, and when replacement is needed. Thus, the system can degrade gracefully and prevent the robot from wearing itself out.
    - Accuracy of computer vision can also degrade over time due to scratches on the lens or dust penetration. There is nonlinear behaviour at the boundary conditions as there's little middle ground to detecting something in computer vision; again calibration tests can help replace the part before it degrades too severely.

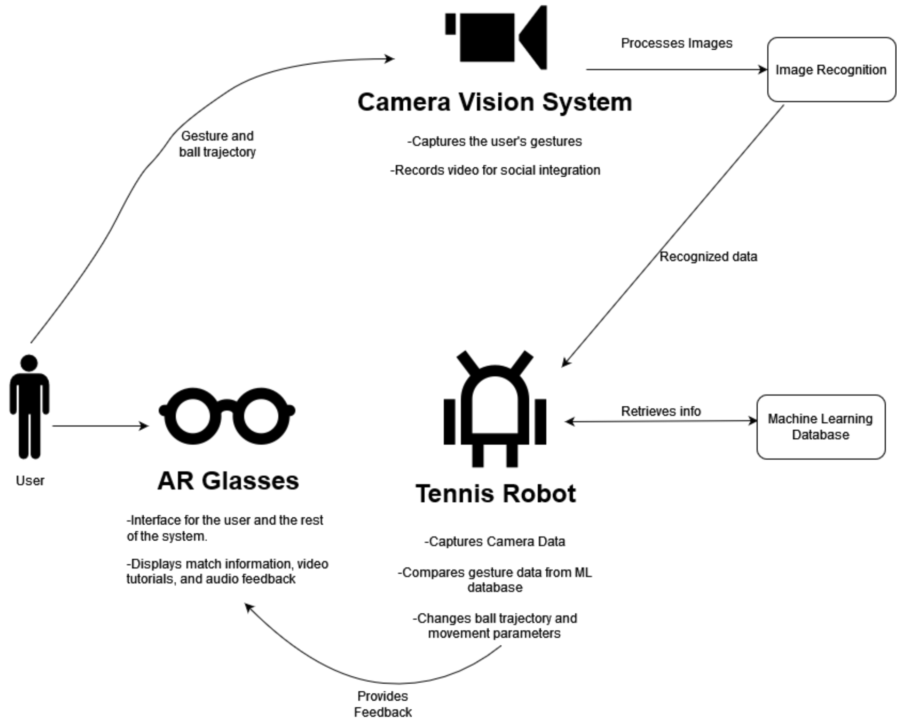


Figure 2: System Architecture Diagram

- All battery-powered devices (if charged and handled correctly) will degrade linearly, but the important thing is to keep the user informed of battery health via the user interfaces.

2. **Elegance:**
   - Unified integration of AR glasses, tennis ball robots, and cameras provides the user with a unique training experience, regardless of their skill level. Thus it would be important to match the design language of these 3 components.
   - Problems that would harm the experience would be interference between the 3 components, whether it's harsh lighting on the camera, rainy weather, etc. Thus, it'd be best to start in indoor environments where external factors like these can be controlled.

3. **Balance:**
   - There will be similar user interfaces on the robot, camera app, and AR glasses in terms of controls, and for recordings to be shared on social media.
   - Because all 3 components are meant to be used together, no one component shall be able to do everything and thus negate another. For example, there's no need for the robot to connect to social media, as all the social integration is done via the camera app, which provides focused App development.

4. **Growth Capability, Scalability, and Extensibility:**
   - Expandable machine learning database can offer evolving techniques.
   - Additional software updates can offer better instructions/tutorials and detection accuracy.
   - Additional tracking systems can be added so more than one user can train.

- Other components can be integrated easily.

5. **Visibility:**
   - App can set the parameters of the robot and AR glasses.
   - Both the robot and the camera must have visible error-signalling LEDs in case of hardware failure. In case of player injury, speakers on the robot can be used as alarms to get the attention of nearby people.
   - The robot can be opened and adjusted mechanically in the case of maintenance or jam.

6. **Reasonableness:**
   - We can leverage existing technology (computer vision algorithms for detection [5], AR glasses, AR development kits [6], robotic tennis ball shooting mechanisms [7] already exist).
   - Further developments in AI and assistant technology can allow a more personalized user experience when training.

7. **Complexity:**
   - The AR, App and robot are decoupled; each can be used, fixed, and adjusted as a standalone product.
   - Intuitive user interface for easy understanding of using the AR.
   - Tennis instruction for the users via sounds (App) and vision (AR)

5 Modeling and Simulation

Because this system is centered around 3 vital components: the robot, the camera, and the AR glasses, it would be best to model them individually (whether by a simulation or a closed environment test). Once their individual functional requirements have been tested, we can add another system to see how well it pairs, and if the individual requirements can still be met. This is essentially following the system architecture diagram mentioned previously, with testing of the requirements in a controlled environment.

1. **Tennis Robot:** Some of the functional requirements were max serving speed, various degrees of freedom, maximum height, etc. This can be tested in a closed environment with additional sensors. Adding the camera model (with its machine learning algorithm) introduces a range of inputs and outputs to and from the robot, which can change it's parameters such as frequency of serves, trajectory of next shot, movement speed, etc. Adding the AR glasses would require an additional interface on the robot for wireless control, which would need to have low latency during an emergency stop.

2. **Camera Vision System:** The requirements were recognizing body movements from the user, tracking the tennis ball, user, and passers-by, and sending information to the Machine Learning algorithm. All of this would need to be individually tested for accuracy, precision, and general response time. It would also preferably be in a closed environment, with varying parameters such as lighting conditions, different user clothing, net sizes, and court boundary lines. Adding the robot system would require an additional interface to transport the outputs of the camera system as inputs to the robot. Interfacing the AR glasses are necessary for recording a match and displaying tips when the machine learning algorithm recognizes technique issues.

3. **AR glasses:** The requirements of this were to display HUD elements (showing match information), overlay the robot with another person, and display tutorials of proper techniques. This system doesn't have many functions on its own but can be looked at as a large interface from the user to the overall system.

An easier way to visualize this functional model is with a table, with inputs, outputs, states, and transformation rules. Here, states are what guide the inputs and outputs, and transformation rules is how the system would interpret data at a high level.

Table 1: Functional View of Systems

System	**Inputs**	**Outputs**	**States**	**Transformation Rules**
Tennis Robot	Machine learning outputs	Ball trajectory and shooting	Training	Uses gesture outputs to mimic real player
	Control prompts from other systems	Change in movement speed	Real match	Adapts to user technique
Camera Vision System	User Movements	Gesture reading	Tracking	Identifies different techniques from database
	Ball tracking		Recording	
AR glasses	User prompts	Display match info.	Passive	Helps user think they're playing with real person
	Machine learning outputs	Show tutorials	Active	

6 Technology Readiness Level (TRL)

The proposed technology for the robot tennis coach can be assessed at a relatively high TRL (between TRL 6 and TRL 7). This is because the integration of various components such as cameras, image recognition software [5], tennis ball machines [7], and AR [6] is feasible and can be achieved using existing technologies.

The following steps could be taken to bring the product to a higher TRL:

1. Prototype Testing (TRL 7): Building a functional prototype and conducting field tests with tennis players to assess the effectiveness of the system in real-world scenarios.

2. System Qualification (TRL 8): Making improvements based on user feedback and refining the system for commercial use.

3. Regulatory Compliance (TRL 9): Ensuring that the technology complies with relevant regulations, i.e. safety standards and data privacy laws.

7 Benchmarking

Because this product is so unique, there currently isn't a direct competitor on the market. Therefore, it'd be wise to benchmark against existing tennis training tools and coaching services to assess the unique advantages and capabilities of AceMaster.

1. **Coaching Services:** This would be the average cost of a tennis coach in a given area. There's many advantages in getting a tennis coach, namely the personalized training, emotional trust/bond between people, and being able to just play a match. That last point is important, as our product solution isn't playing with someone, but rather training them to be better. There currently is an autonomous tennis training robot on the market that one could play tennis with and train, but the cost of it currently is high enough that regular people would just hire a coach. On the other end, there's tennis ball machines that just shoot balls so the user can practice alone. Our solution hopes to take the middle ground between these two, and provide a solution that offers real feedback not accessible from a tennis ball machine, but with the availability and patience not accessible from a tennis coach.

2. **Tennis ball machines:** This would be how effective a standard tennis ball machine is at training the user to get better at tennis. In the System Competitive Analysis section we look at the tennis tutor machine, which advertises itself as a training machine, although the user would already need to have some skill in tennis to use it properly and get better at it. A complete novice at tennis would have difficulty keeping up with the machine, and wouldn't realize when they've made a tennis fault. Additionally, these machines cost a decent amount, meaning no beginner in tennis would be the target audience. We believe that by offering our product to gyms and clubs, letting people test and train with the machine offers a better value proposition for a much larger audience than the tennis ball machines.

3. **Inertial measurement unit (IMU):** These would be small devices inserted into tennis rackets that collect information on forces, moments, and motion of the racket, giving information about how often the user is hitting the "sweet spot". While there are lots of competitors on the market (the System Competitive Analysis section talks about Zepp Tennis 2 for example), they have the same problem as the tennis ball machines: not providing enough useful information to novices. While it would sound logical to incorporate IMU's as a component in our system, currently the sensor technology isn't as accurate at a low enough cost to keep our product competitive, so it would be best to consider it in the future.

8 Mistake Proofing

This section is about using the components of the system to automatically detect errors (whether in the system or by the user). This is done by looking at the System Architecture Diagram, brainstorming about what could go wrong at a given interaction, isolating the components, and thinking of ways to make that error impossible. This isn't necessarily about eliminating certain interactions; it could include alternative interactions, or having a high visibility of system information, so the user is well informed.

1. User-Friendly Interface: Design the user interface for all 3 components (similar icons, graphs, etc) so the user can transfer what they've learned, and know the component's interdependence. This should make clear the limitations of the components, like the mobile app and AR glasses

not being able to work simultaneously when in training, limiting distractions and keeping the user focused.

2. User Training: Provide basic training to users on how to operate the machine, and to the staff on how to maintain the system properly. For example, in the event of a ball jam in the robot, special instructions should be written, so the user only has one way to remove said ball, and not interfere with another system. Also, visible calibration tests can help the user see the system in action.

3. Safety Protocols: Implement safety features that automatically shut down the system in case of any malfunctions or unsafe conditions, such as when a passer-by enters the court, or if the user gets hit by a ball.

9 Verification and Validation

9.1 Verification

This is about ensuring each component of the system performs according to design specifications through testing and analysis. This would include component and redundancy testing, using the functional modelling and simulation mentioned previously.

As mentioned before, component testing would be done individually in a closed environment. The robot is tested for movement speeds and ball trajectories, which could be by time based recordings, or even a radar gun. The camera system would be tested based on accuracy requirements, if it can reliably keep the lens in focus, and if the cameras can both verify a point of reference in their viewfinder. The AR glasses, while just acting as an interface for the user, also needs to be tested for wireless communication strength, glare problems, and latency. That last part is extremely important, as the ball is going at very high speeds, and the user's view must not be obstructed when that happens. Lastly, once all the components and external sub-systems (like the mobile app) have been tested, additional testing of redundancies would need to be carried out, like the system being able to run with one camera if another goes offline.

9.2 Validation

This is about confirming the system meets the user's needs, and effectively improves their tennis skills through real-world player feedback. These would include design requirements mentioned earlier, like reliability, safety, and a good training experience.

Because some of the requirements have some subjective qualities (like the system correcting technique issues the same way as a coach), there'd need to be verification tests done by a large sample size of tennis coaches, to accommodate users of various stages in training. Additionally, wicked problems, such as that of Machine Learning and gesture recognition issues, can only be understood while the system is in development. This means that some objective criteria for evaluating the system may not be met initially, so testing would have to be done in phases.

9.3 Both

In between these 2 would be modularity and integration testing. The former is all about how many additional components, like cameras and robots, we can add before the system doesn't work properly.

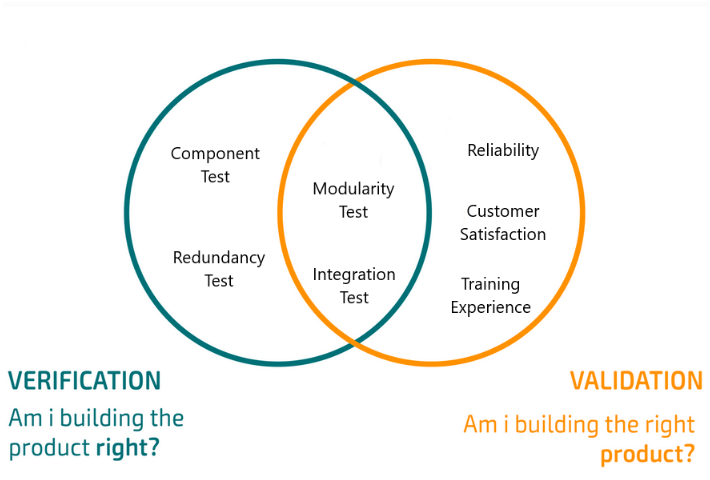


Figure 3: Verification and Validation Diagram

The latter is about how well those components interact with each other, and if that ultimately leads to a better training experience. For example, adding an additional camera should help with gesture recognition and ball tracking, but it has the possibility to alter video feeds coming from another camera, messing with the Machine Learning algorithm.

10 System Optimization

Some of the design variables of this product would be cost, weight, ball capacity, battery run time, data storage, data transmission speeds, etc. These are physical variables, so to maximize one, we would need to put a constraint on another. Because our product can be classified as a "complex system", it would be best to use object decomposition to break the system into the 3 components as mentioned previously. Optimizations can be done on an individual component level, and be tested when the system is assembled again. This would provide a range of non dominated solutions so a good compromise can be made when comparing competitor offerings.

Let's say as an example we fix the number of tennis balls the system can operate at any one time, and we change other design variables within their own minimum and maximum ranges. Once we've come to an acceptable compromise that retains the functional requirements of the tennis ball robot, we combine it with a range of other fixed-variable variations of the camera and AR system. This would provide a range of solutions to be evaluated by the elements of concept architecting. If we fixed the number of tennis balls in our system, we may not score greatly on growth capability, as the user can only train for a fixed amount of time. However, we can do well in elegance and visibility, as the user will always know when the system is out of tennis balls, and has a general understanding of the limitations of the system.

Another thing to consider are "soft" variables. Because this product is meant to adapt to user techniques and improve via user feedback, substantial software research and development would be needed after the product releases. This would be in the form of software updates that improve AR tracking, offer better tutorials, and more accurate gesture tracking. This can realistically only happen if enough businesses are expressing interest to buy and use the product on a continuous basis. To optimize these software variables, a constraint would be needed to be put on after-sales revenue, or some sort of recurring cost. This could be in the form of different pricing models, such as subscriptions for gyms or private clubs.

11 System Competitive Analysis

As mentioned in benchmarking, there currently isn't a direct competitor in our space, outside of an actual tennis coach. What we can look at, is similar product offerings based on our 3 functional components, and analyze their feature set to gauge a potential customer base.

11.1 Tennis Tutor Plus

This is a traditional portable tennis ball machine that most people think of when they're practicing by themselves [8]. It hosts a slew of nice features, such as a top tennis ball speed of 85mph, 150 ball capacity, fold out towing handle, built-in oscillator, and more. It also has a remote for controlling the machine at a distance, with the same controls as on the side of the machine. There's even an app that mirror the controls of the remote, so it's well thought out. The price range varies based on what feature set you want.

Figure 4: Tennis tutor machine

This is an interesting product, not only because it's serving a customer base very similarly to our target audience, but also because it's been around for a long time, meaning that customers trust it. The only way we can hope to set foot in this market is with a killer feature, and that would hopefully be the system's ability to correctly identify tennis faults and offer feedback. Additionally, because of it's price-point and marketing towards individuals rather than other businesses, leaves an opening in the market. Because of the continuous improvement of the Machine Learning algorithm, we can advertise overall value to a business over a period of time, by letting them charge customers on some time basis.

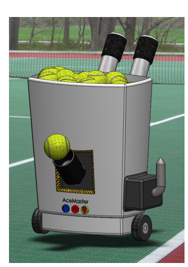


Figure 5: Acemaster CAD drawing

Additionally, we can update the look of the machine to be more modern instead of being so boxy, and to justify a competitive price. We've even made a CAD drawing to visualize our concept.

11.2 Playsight PRO

This is called a "Smartcourt" solution, that offers different cameras and broadcasting services for recording, tracking, and live-streaming professional sports [9]. The idea is that by placing these cameras across a court, it would transform it into a professional environment, ready to be broadcasted onto TV networks. It also has player tracking, graphic overlays, scoreboard integration, and most importantly, real time feedback validated by real tennis coaches. They also allow you to download an app and use your phone's camera for their services.

Figure 6: Playsight PRO

Realistically, we don't view this service as a competitor, but hopefully as a joint partner. They already have the expertise and market base in vision analysis, and a partnership with them would be mutually beneficial; Playsight can expand into machine learning automated devices, and we can use their tracking and gesture data to give our system really good training capabilities.

Should this not be the case, we'd need to rely on open source vision system software, and work out the kinks of finding tennis faults by ourselves. We can use the same strategy as Playsight here and use this as a marketing opportunity. Essentially, we can hold amateur tournaments in gyms to collect large amounts of data, and have tennis coaches provide insight. We can then use this insight in developing the Machine Learning algorithm, while also marketing off the event.

11.3 Zepp Tennis 2

This is a swing and match analyzer that can be attached to a tennis racquet to track key performance metrics for each swing, including stroke type, ball speed, ball spin, sweet spot, and more [10]. It's essentially an IMU that connects to the user's phone via bluetooth, and tells the user how often they're hitting the tennis ball at the "sweet spot".

While simplistic, this product can actually be very helpful in our system to track the user and find tennis faults. However, reviews of this product show faults in bluetooth connections, user interface issues, and app crashes. At the time of writing, it's allegedly discontinued from the manufacturer, making the bluetooth sensor useless.

Despite being discontinued, we can learn something from the mistakes of it's manufacturer. The first being that we have to offer some sort of offline capability of our system so it won't be bricked if the servers come down. Additionally, it's important to have good app connectivity and integration, so reliability of wireless communications will be paramount. While incorporating an IMU in our system would sound logical, the meddling reception of products like these, in addition to the risk of it lowering our system reliability, makes us hesitant to venture into this technology for now.

Table 2: Product Feature Comparison Table

Feature	**Our Product**	**Tennis Tutor Plus**	**PlaySight PRO**	**Zepp Tennis 2**
Vision Analysis	✓		✓	
Correct Techniques	✓		✓	✓
Traditional Ball Machine	✓	✓		
Augmented Reality (AR)	✓			
Mobile App Integration	✓	✓	✓	✓
Price	Competitive	High	Medium	Medium
User Experience	Excellent	Good	Good	Low

12 Risk Assessment

12.1 Technology Failure

The risk associated with technology failure, specifically in the camera or image recognition software, is a considerable concern due to its potential to disrupt the core functionality of the system. Regular system maintenance is essential to address this, as it enhances the reliability of these critical components. Redundancy measures, such as backup systems, are necessary to ensure continuous operation even if one component fails.

12.2 User Privacy

With the growing sensitivity around personal data, the risk related to user privacy is a valid concern, and the potential impact, likelihood, and severity are all assessed as moderate. Still, given the increasing scrutiny and legal implications surrounding data handling, transparent practices and explicit user consent are not just ethical but also crucial for building trust. Mitigating this risk ensures compliance with privacy regulations and boosts a positive user experience.

12.3 Equipment Malfunction

The moderate risk associated with the mechanical failure of the ball machine is grounded in the potential disruption to the training sessions. Regular maintenance is the common approach to prevent unexpected breakdowns, ensuring the system's reliability. Having backup equipment readily available adds an extra layer of preparedness, minimizing downtime and user frustration.

12.4 AR and Mobile App Issues

Issues like app crashes or compatibility problems can impede user experience and system functionality. They carry a moderate risk. While the likelihood and severity are low, regular updates to the mobile app should be implemented to address bugs, improve performance, and ensure compatibility with evolving technologies. Thorough compatibility testing is crucial to identify potential issues before they impact users.

12.5 User Injury

The high risk and high severity associated with user injuries from tennis ball interactions is intuitive, given the physical nature of the activity. Implementing safety measures, including user training and protective gear, aligns with the common approaches to minimize the potential harm to users. So even with a low likelihood. a proactive stance is needed to not only ensure user safety but also safeguard against potential legal consequences and reputational damage.

Table 3: Risk Assessment Table

Risk Category	**Description**	**Potential Impact**	**Likelihood**	**Severity**	**Mitigation Strategy**
Technology Failure	Camera or image recognition software failure	High	Moderate	High	Regular system maintenance, redundancy
User Privacy	Concerns about personal data collection	Moderate	Moderate	Moderate	Transparent data handling, user consent
Equipment Malfunction	Mechanical failure of the ball machine	Moderate	Low	Moderate	Regular maintenance, backup equipment
AR and Mobile App Issues	App crashes or compatibility issues	Moderate	Low	Moderate	Regular app updates, compatibility testing
User Injury	Tennis ball-related accidents or injuries	High	Low	High	Safety measures, user training, protective gear

13 Margins and Contingency

13.1 Response Time

The evaluation of response time indicates the dynamic nature of technical estimations during a system's development cycle. As the design matures, the current best estimate of response time improves from 10 milliseconds. The ≈ 4 millisecond margin takes into account the gap between the maximum expected value (5 milliseconds) and the greatest possible value (1 millisecond). The ≈ 5 millisecond contingency provides a safety buffer while admitting the possibility of future development.

13.2 Analysis Speed

The analysis speed, measured in frames per second (fps), illustrates the iterative nature of system development. The current best estimate of 24 fps (the common fps to guarantee the fluency of a video) is likely to evolve, with the margin of 30 fps allowing for flexibility. The contingency of 6 fps acts as an educated measure, allowing potential enhancement in the analysis speed during the development life.

13.3 Hits per Minute

For hits per minute, the current best estimate of 40 hits reflects the team's understanding at this point (more or less a professional player's level), with a margin of 20 hits providing room for potential improvements beyond the maximum expected value of 80 hits. The contingency of 40 hits acknowledges the inherent uncertainty in predicting hits per minute during the development phase.

13.4 Ball Capacity

In terms of ball capacity, the current best estimate of 50 balls is conservative compared to the maximum expected value of 100 balls, with a margin of 20 balls. The contingency of 50 balls allows for adjustments in the system's ball-handling capabilities during the ongoing development process.

13.5 Move Speed

The move speed in meters per second is the key for the robot to move on the court like a real player. The current best estimate of 1 m/s is expected to see growth, as indicated by the margin of 1 m/s. The contingency of 1 m/s acknowledges that further boost to speed may be realized during the development life.

13.6 Data Storage

Considering data storage in terabytes, the current best estimate of 1 TB is based on the team's understanding, with a margin of 5 TB allowing for potential growth beyond the maximum expected value of 5 TB. The contingency of 4 TB acknowledges the need for flexibility in accommodating unforeseen data storage requirements during development.

13.7 Average Data Rate

The assessment of the average data rate in gigabits per second reflects the ongoing improvement of the system's capabilities to ensure the fast response of the system. The current best estimate of 1 Gbps is conservative compared to the maximum expected value of 2 Gbps, with a margin and contingency both set at 1 Gbps. This allows for adjustments as the team fine-tunes the system's data transmission capabilities during the development life.

14 System Reliability

In our tennis training system, reliability is assessed with these key metrics:

- **MTTF**: MTTF reflects the average time a component operates before a failure. Critical components like the Image Recognition Software and Tennis Ball Machine are designed with high MTTF values to ensure prolonged and reliable operation.
- **MTBF**: MTBF measures the average time between failures and repairs. The system has a high MTBF, as all components have relatively high reliability.

Table 4: Technical Resource Assessment Table

Technical Resource	Current Best Estimate	Maximum Expected Value	Maximum Possible Value	Margin	Contingency
Response Time (ms)	10	5	1	-4	-5
Analysis Speed (fps)	24	30	60	30	6
Hits per Minute	40	80	100	20	40
Ball Capacity	50	100	120	20	50
Move Speed (m/s)	1	2	3	1	1
Data Storage (TB)	1	5	10	5	4
Average Data Rate (Gbps)	1	2	3	1	1

- **Useful Phase**: The useful phase represents optimal performance. Components like the Mobile App and Audio Feedback System enhance this phase, ensuring a positive user experience.
- **Wear-Out Phase**: The wear-out phase may occur when the system ages, especially for mechanical components like the Tennis Ball Machine. Maintenance is required to prevent performance decline and extend their lifespan.

14.1 Image Recognition Software

The Image Recognition Software, being integral to our system, analyzes player movements in real-time. Its low failure possibility is attributed to the maturity of machine learning technology, robust programming and extensive testing. However, the complexity of debugging machine learning software and ensuring seamless integration with the overall system makes the time to fix issues lengthy.

14.2 Tennis Ball Machine

The Tennis Ball Machine is responsible for delivering balls with diverse settings. It has a low likelihood of failure due to its technology maturity and reliability (on the market for years, TRL 9). The potential adjustments needed to be fixed in the mechanical components require moderate time.

14.3 Audio Feedback System

The Audio Feedback System, designed to provide instant guidance to players, has a low likelihood of failure thanks to careful development and testing. The system's straightforward audio output pathways and minimal dependencies make the time to fix issues related to this component short.

14.4 Mobile App

The Mobile App, enhancing engagement and social features, has a low failure probability which can be achieved by rigorous coding and testing. Rapid resolution time is possible if the development follows a modular design [11], which allows for swift identification and correction of any issues.

14.5 Continuous Learning

The Continuous Learning component, incorporating player feedback for system improvement, carries a moderate failure probability due to the dynamic nature of user inputs and the relative novelty of the technology, *active learning* (TFL 6) [12]. The intricate process of analyzing user feedback to identify the issues in this component can extend resolution time greatly.

Table 5: Component Failure Assessment Table

Component	**Description**	**Failure Possibility**	**Time To Fix**
Image Recognition Software	Analyzes player movements and gestures in real-time.	Low	Long
Tennis Ball Machine	Shoots balls with varying speed, spin, and trajectory.	Low	Moderate
Audio Feedback System	Provides instant feedback to the player with audio suggestions.	Low	Short
Mobile App	Enhances engagement and provides social features.	Low	Short
Continuous Learning	Incorporates player feedback to improve the system over time.	Moderate	Long

15 Conclusion

To conclude, we hope the Acemaster Tennis training robot will revolutionize the way we train and play tennis. Of course as technology grows better and cheaper, better solutions such as a fully automated robot to play tennis with may be a real possibility. Even then, however, this product can stay relevant due to it's personalized improvements with each user thanks to the Machine Learning, which gives it a more human quality. Ultimately, our goal is for the customer sentiment to see this as a "new way to train and play tennis", rather than playing against an advanced robot. Additional social features such as overlaying the robot with real athletes, and social media integration will hopefully cement this product in history.

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