Augmented Reality Implementation Framework

Kristen Phan

MSc Business Information Technology

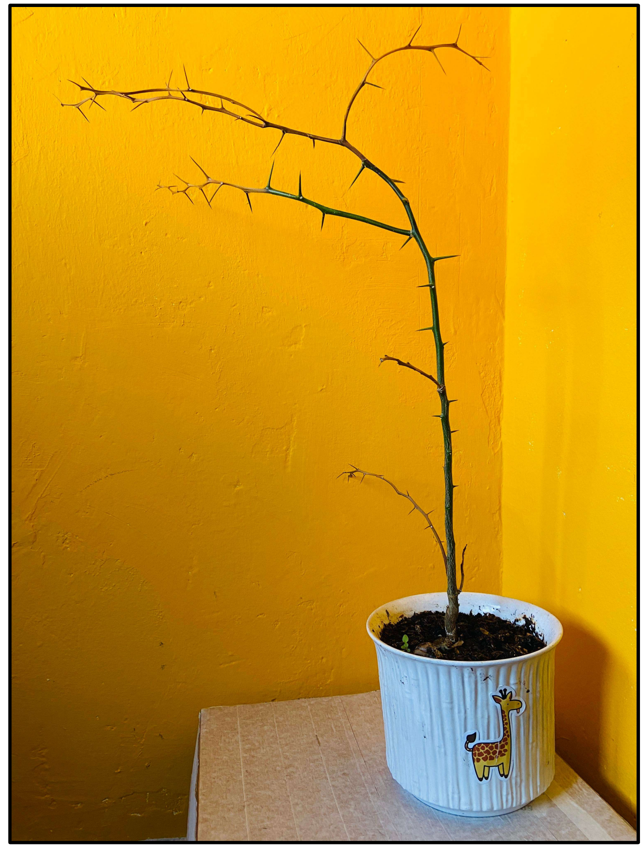
Supervisor: Ilia Shakitko

January 2023

LIQUID STUDIO.NL
BE DIFFERENT
UNIVERSITY OF TWENTE. accenture

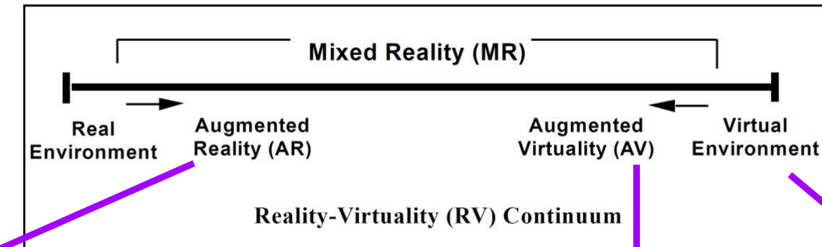
What Can We Do About Kristen's Green Thumb Problem?

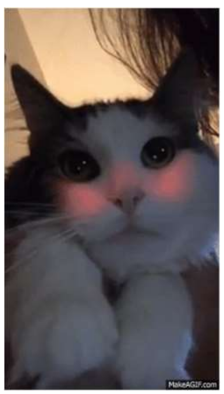
Before



Now: Dead

Augmented Reality (AR) 101: Mixed Reality Spectrum





Source: P. Milgram, H. Takemura, A. Utsumi, and F. Kishino, "Augmented reality: A class of displays on the reality-virtuality continuum," in Telemanipulator and telepresence technologies, 1995, vol. 2351: Spie, pp. 282-292.
Photo credits:
https://gfycat.com/animatedmadbobcat
https://observer.com/2022/10/microsoft-teams-goes-virtual-and-avatars-finally-get-legs-as-mark-zuckerberg-announces-new-metaverse-developments/
https://www.rtlnieuws.nl/tech/artikel/5264551/microsoft-stort-zich-op-metaverse-teams-krijgt-live-3d-avatars

AR: How Does It Work?

Two technologies underpin AR:

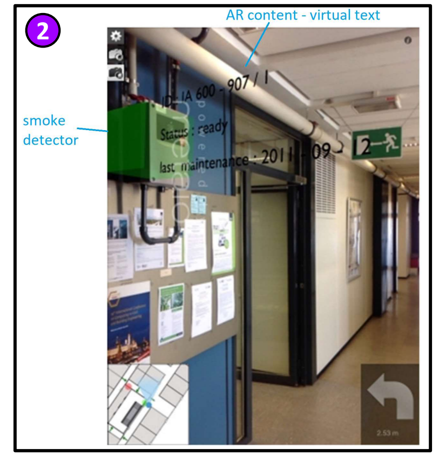
- *Tracking engine = Tracking the location + orientation of a physical object/ environment from live camera feed.*
- *Rendering engine = Displaying a virtual object as anchored to the physical object/ environment*

Common tracking techniques:

1. Fiducial/ image marker: 2D images
2. Object: 3D objects
3. Face: Snapchat filters
4. Location
5. Surface: planar surface
6. Spatial: 3D mesh of an environment
7. Others: Depth, hand, eye, body, head, controller tracking

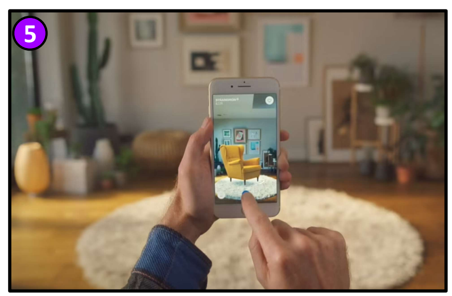
1

2



4

5



https://www.ikea.com/au/en/customer-service/mobile-apps/say-hej-to-ikea-place-pub1f8af050

6

AR 101: AR Platforms – Native AR v. WebAR v. AR Headset

Each AR platform has its capabilities and limitations.

Native AR + WebAR

> Native AR apps: Downloaded to and installed on user device.
> WebAR apps: Run directly from web browser; Sharable through an URL.

A virtual recipe book rendered on the physical label of a Heinz ketchup bottle.

AR Headset

> Requires dedicated hardware: HoloLens, Magic Leap, etc.
> Has built-in tracking capabilities (hand, eye, head, hand-held controller tracking) + can integrate external tracking engine.

Colleagues collaborate remotely via video call on a HoloLens headset.

Source: https://www.blippar.com/ar-studio; https://dynamics.microsoft.com/en-gb/mixed-reality/remote-assist/

AR 101: AR Platforms – Native AR v. WebAR v. AR Headset

Each AR platform has its capabilities and limitations.

Native AR + WebAR

> Native AR apps: Downloaded to and installed on user device.
> WebAR apps: Run directly from web browser; Sharable through an URL.

A virtual recipe book rendered on the physical label of a Heinz ketchup bottle.

AR Headset

> Requires dedicated hardware: HoloLens, Magic Leap, etc.
> Has built-in tracking capabilities (hand, eye, head, hand-held controller tracking) + can integrate external tracking engine.

Colleagues collaborate remotely via video call on a HoloLens headset.

Source: https://www.blippar.com/ar-studio; https://dynamics.microsoft.com/en-gb/mixed-reality/remote-assist/

AR 101: AR Platforms – Native AR v. WebAR v. AR Headset

Each AR platform has its capabilities and limitations.

Native AR + WebAR

> Native AR apps: Downloaded to and installed on user device.
> WebAR apps: Run directly from web browser; Sharable through an URL.

A virtual recipe book rendered on the physical label of a Heinz ketchup bottle.

AR Headset

> Requires dedicated hardware: HoloLens, Magic Leap, etc.
> Has built-in tracking capabilities (hand, eye, head, hand-held controller tracking) + can integrate external tracking engine.

Colleagues collaborate remotely via video call on a HoloLens headset.

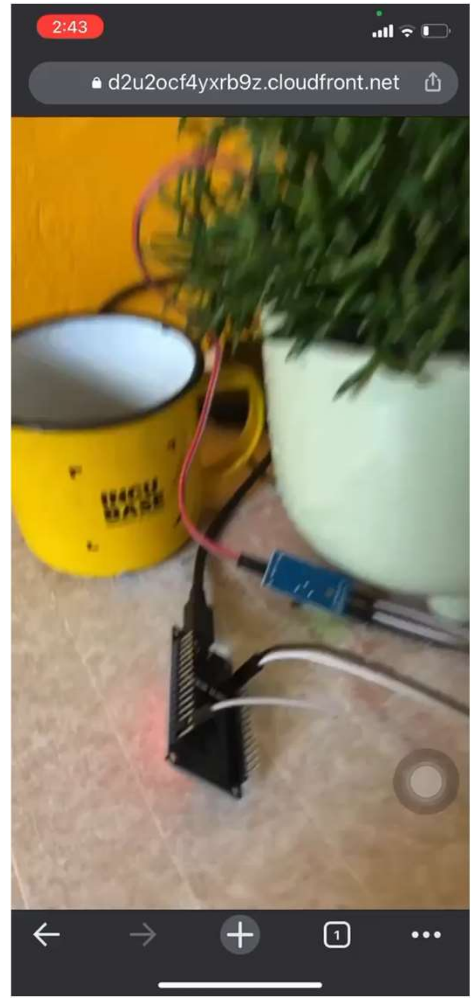
Source: https://www.blippar.com/ar-studio; https://dynamics.microsoft.com/en-gb/mixed-reality/remote-assist/

WebAR Prototype: Show Don't Tell

Image marker

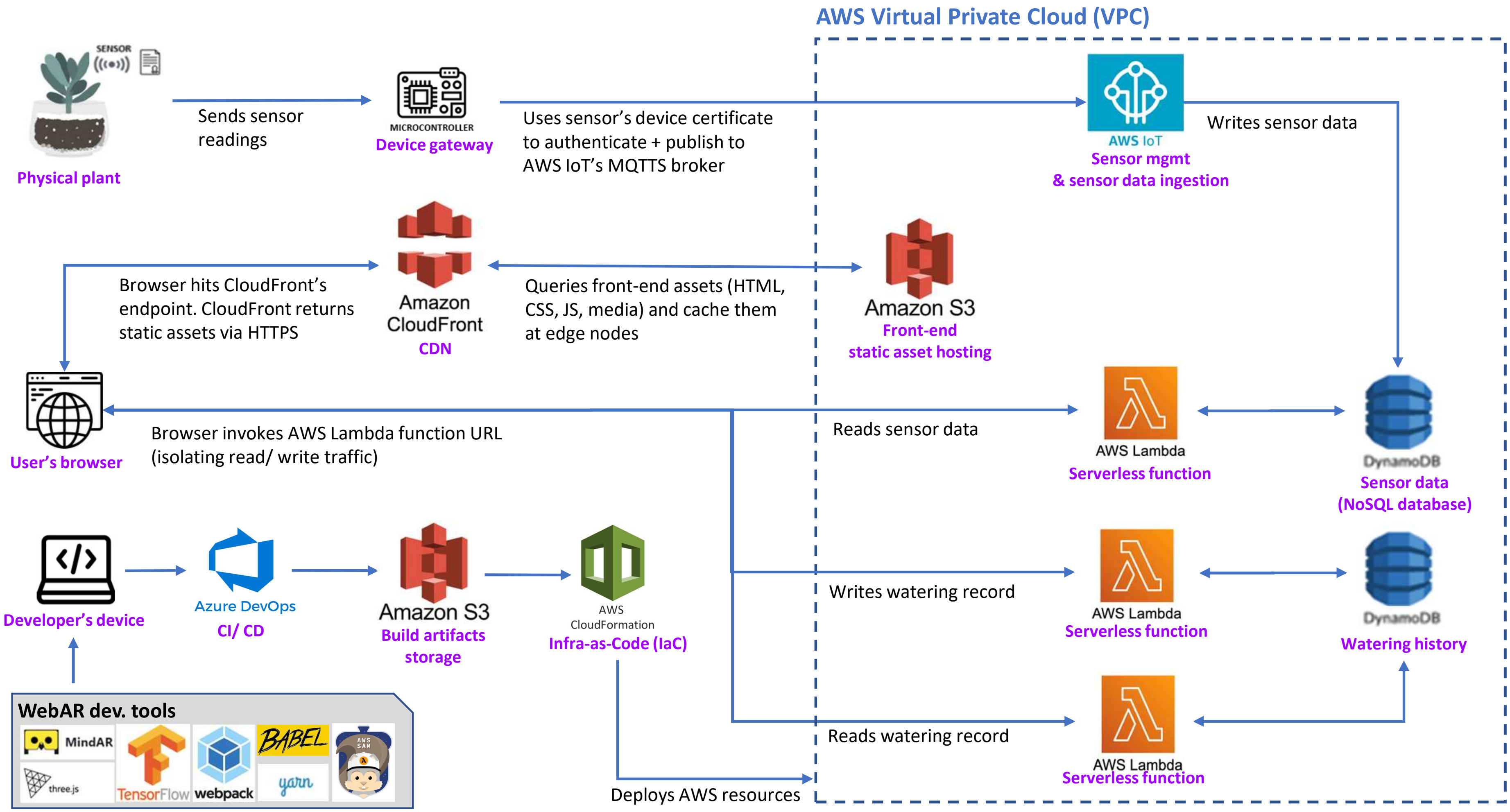
Soil moisture sensor

Microcontroller connected to sensor



Repo: https://dev.azure.com/liquidstudio-nl/WebAR

WebAR Prototype: Serverless Architecture



Frontend Code Deep Dive: Tracking + Rendering + TensorFlow (1/2)

The tracking engine (MindAR), rendering engine (three.js), and TensorFlow pre-trained gesture recognition model (fingerpose) all run in the browser.

```
// ./FRONTEND/SRC/INDEX.JS
// Initialize MindAR tracking engine
const mindarThree = new window.MINDAR.IMAGE.MindARThree({
      imageTargetSrc: "../assets/targets/ls.mind", // image marker ...});

// Initialize Three.js rendering engine
const {scene, camera, renderer, ...} = mindarThree;

// Load a 2D dashboard as anchored to target image
const dashboard = new CSS3DObject(document.getElementById("dashboard"));
const anchor = mindarThree.addAnchor(...);
anchor.group.add(dashboard);

// Start MindAR tracking engine
await mindarThree.start();
renderer.setAnimationLoop(() => {
  // Reposition dashboard for every frame so that the dashboard faces the camera
  dashboard.lookAt(camera.position);
  // Re-render scene as camera position is updated
  renderer.render(scene, camera);
});
```

Frontend Code Deep Dive: Tracking + Rendering + TensorFlow (2/2)

The tracking engine (MindAR), rendering engine (three.js), and TensorFlow pre-trained gesture recognition model (fingerpose) all run in the browser.

```
// Initialize fingerpose (pre-trained tensowflow ML model) for gesture detection
const model = await handpose.load();
const thumbsUpGesture = new fp.GestureDescription(...); // define a gesture
const GE = new fp.GestureEstimator([thumbsUpGesture]); // define a gesture estimator

// Run fingerpose model to detect a pre-defined gesture in video frames
const cameraStream = mindarThree.video;
const detect = async () => {
    const predictions = await model.estimateHands(cameraStream);
    if (predictions.length > 0) { // if a hand is detected
        const estimatedGestures = GE.estimate(...)
        const best = estimatedGestures.gestures.sort(...) // find the best detected gesture
        if (best.name === 'thumbs_up') {
            // Invoke Lambda to record a new watering record with plantStatus = "Good"
        }
        ...
    }
}
window.requestAnimationFrame(detect);
```

AR Implementation Framework: 3 Key Questions to Answer

PROCESS SUITABILITY FOR AR

Can and should a business process be enhanced with the use of AR?

AR PLATFORM SUITABILITY

Which AR platform (WebAR v. native AR v. AR headset) is most suitable for the process?

AR DEV. TOOL SUITABILITY

Which tracking + rendering engines are suitable for the select process and AR platform?

AR Implementation Framework: 3 Key Questions to Answer

PROCESS SUITABILITY FOR AR

Can and should a business process be enhanced with the use of AR?

AR PLATFORM SUITABILITY

Which AR platform (WebAR v. native AR v. AR headset) is most suitable for the process?

AR DEV. TOOL SUITABILITY

Which tracking + rendering engines are suitable for the select process and AR platform?

AR Implementation Framework: 3 Key Questions to Answer

PROCESS SUITABILITY FOR AR

Can and should a business process be enhanced with the use of AR?

AR PLATFORM SUITABILITY

Which AR platform (WebAR v. native AR v. AR headset) is most suitable for the select process?

AR DEV. TOOL SUITABILITY

Which tracking + rendering engines are suitable for the select process and AR platform?

AR Implementation Framework: 3 Key Questions to Answer

PROCESS SUITABILITY FOR AR

Can and should a business process be enhanced with the use of AR?

AR PLATFORM SUITABILITY

Which AR platform (WebAR v. native AR v. AR headset) is most suitable for the process?

AR DEV. TOOL SUITABILITY

Which tracking + rendering engines are suitable for the select process and AR platform?

AR Implementation Framework

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR

Assess AR platform suitability**:
WebAR vs. Native AR vs. AR-on-headset

Assess AR dev. tool suitability**:
Tracking + Rendering Engine

Refine process requirements

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AGILE*:
DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*

Photo credit: https://www.youtube.com/watch?v=4Vjajj7ZggA

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR → **Assess AR platform suitability**:** WebAR vs. Native AR vs. AR-on-headset → **Assess AR dev. tool suitability**:** Tracking + Rendering Engine → **Refine process requirements**

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

AGILE*:
DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*

Photo credit: https://www.youtube.com/watch?v=4Vjajj7ZggA

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR → **Assess AR platform suitability**:** WebAR vs. Native AR vs. AR-on-headset → **Assess AR dev. tool suitability**:** Tracking + Rendering Engine → **Refine process requirements**

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

AGILE*:
DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR → **Assess AR platform suitability**:** WebAR vs. Native AR vs. AR-on-headset → **Assess AR dev. tool suitability**:** Tracking + Rendering Engine → **Refine process requirements**

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

AGILE*:

DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*

Photo credit: https://www.terrauniversal.com/smart-gas-purged-glove-boxes.html

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR → **Assess AR platform suitability**:** WebAR vs. Native AR vs. AR-on-headset → **Assess AR dev. tool suitability**:** Tracking + Rendering Engine → **Refine process requirements**

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

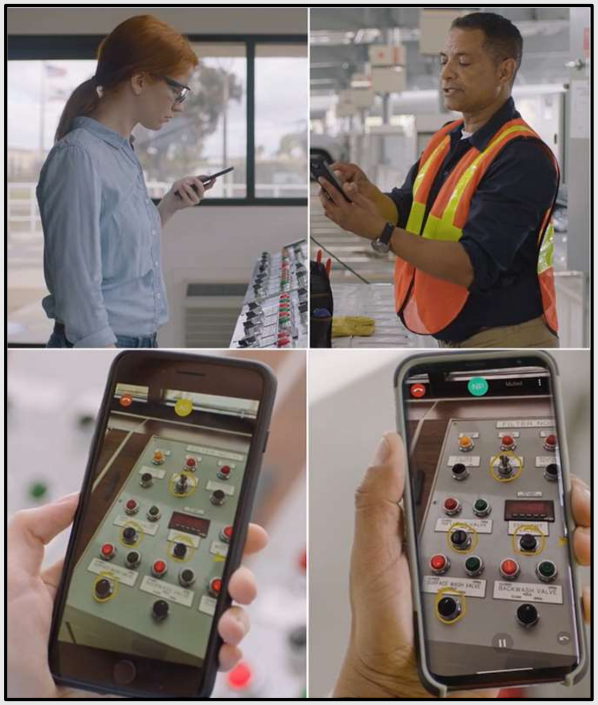
1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue



AGILE*:

DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*

Photo credit: https://www.ptc.com/en/products/vuforia/vuforia-chalk

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR → **Assess AR platform suitability**:** WebAR vs. Native AR vs. AR-on-headset → **Assess AR dev. tool suitability**:** Tracking + Rendering Engine → **Refine process requirements**

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

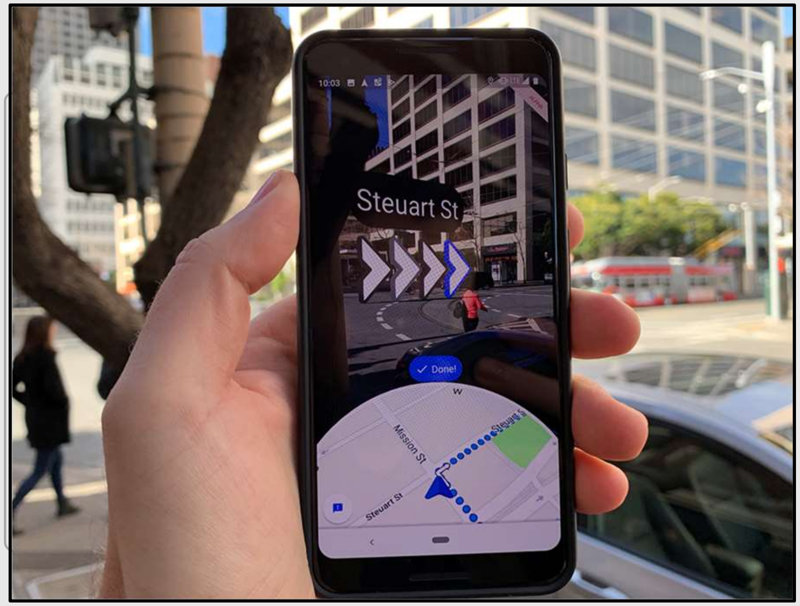
1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue



AGILE*:
DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*

Photo credit: https://techcrunch.com/2020/10/01/google-maps-gets-improved-live-view-ar-directions

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:

- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

1. **Assess process suitability for AR**
2. **Assess AR platform suitability**:** WebAR vs. Native AR vs. AR-on-headset
3. **Assess AR dev. tool suitability**:** Tracking + Rendering Engine
4. **Refine process requirements**

ACTIVITY GUIDANCE

Assess process suitability for AR

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

Assess AR platform suitability

Selection criteria:

1. Usage conditions-specific:
1. Lighting conditions
2. Network connectivity: offline mode support yes/ no
3. Noise
4-5. Temperature + humidity
6-7. Drop-safe + water/dust-proof
8. Health/ safety compliance
9. Hand usage
10. User interactions: hand, eye, headset tracking; voice commands
11. Movement restrictions: e.g., tethered AR headsets cause more restrictions than a phone/ tablet/ non-tethered AR headsets

2. Hardware-specific:
1-2. Battery life + device weight
3. Field-of-view
4-5. Camera + display resolution
6. Refresh rate
7-9. Storage + computation + remote rendering
10. Cross-device development
11. App download required
12. Heat distribution
13. Cost: hardware + subscription

*** Supplemented with Definition Tables + Decision Matrices*

AGILE*:

DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:

- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR → **Assess AR platform suitability**:** WebAR vs. Native AR vs. AR-on-headset → **Assess AR dev. tool suitability**:** Tracking + Rendering Engine → **Refine process requirements**

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

Selection criteria:

1. Usage conditions-specific:
1. Lighting conditions
2. Network connectivity: offline mode support yes/ no
3. Noise
4-5. Temperature + humidity
6-7. Drop-safe + water/dust-proof
8. Health/ safety compliance
9. Hand usage
10. User interactions: hand, eye, headset tracking; voice commands
11. Movement restrictions: e.g., tethered AR headsets cause more restrictions than a phone/ tablet/ non-tethered AR headsets

2. Hardware-specific:
1-2. Battery life + device weight
3. Field-of-view
4-5. Camera + display resolution
6. Refresh rate
7-9. Storage + computation + remote rendering
10. Cross-device development
11. App download required
12. Heat distribution
13. Cost: hardware + subscription

AGILE*:

DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*   *Photo credit:* https://pchubshop.com/product/microsoft-hololens-2-smart-glass-ar/

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR → **Assess AR platform suitability**:** WebAR vs. Native AR vs. AR-on-headset → **Assess AR dev. tool suitability**:** Tracking + Rendering Engine → **Refine process requirements**

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

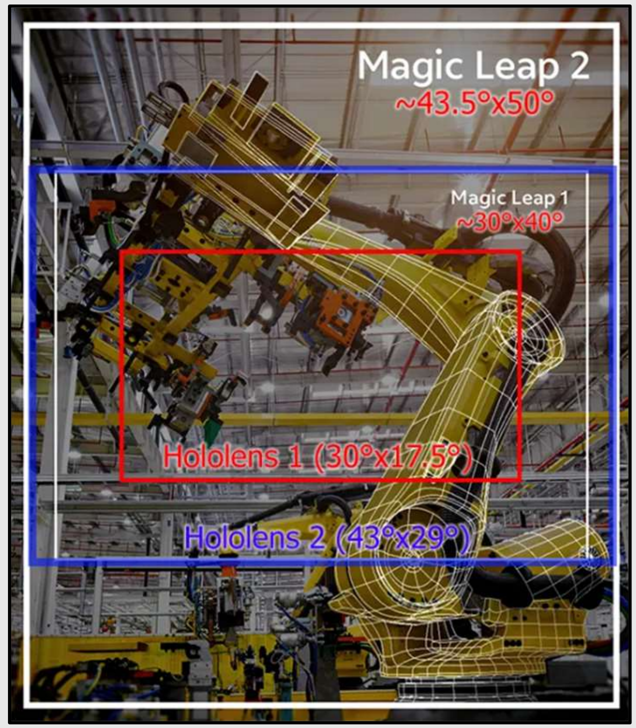
4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

Selection criteria:

1. Usage conditions-specific:
1. Lighting conditions
2. Network connectivity: offline mode support yes/ no
3. Noise
4-5. Temperature + humidity
6-7. Drop-safe + water/dust-proof
8. Health/ safety compliance
9. Hand usage
10. User interactions: hand, eye, headset tracking; voice commands
11. Movement restrictions: e.g., tethered AR headsets cause more restrictions than a phone/ tablet/ non-tethered AR headsets

2. Hardware-specific:
1-2. Battery life + device weight
3. Field-of-view
4-5. Camera + display resolution
6. Refresh rate
7-9. Storage + computation + remote rendering
10. Cross-device development
11. App download required
12. Heat distribution
13. Cost: hardware + subscription



AGILE*:
DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*

Photo credit: https://kguttag.com/2021/10/13/magic-leap-2-for-enterprise-really-plus-another-500m/

AR Implementation Framework

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR

Assess AR platform suitability:**
WebAR vs. Native AR vs. AR-on-headset

Assess AR dev. tool suitability:** Tracking + Rendering Engine

Refine process requirements

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

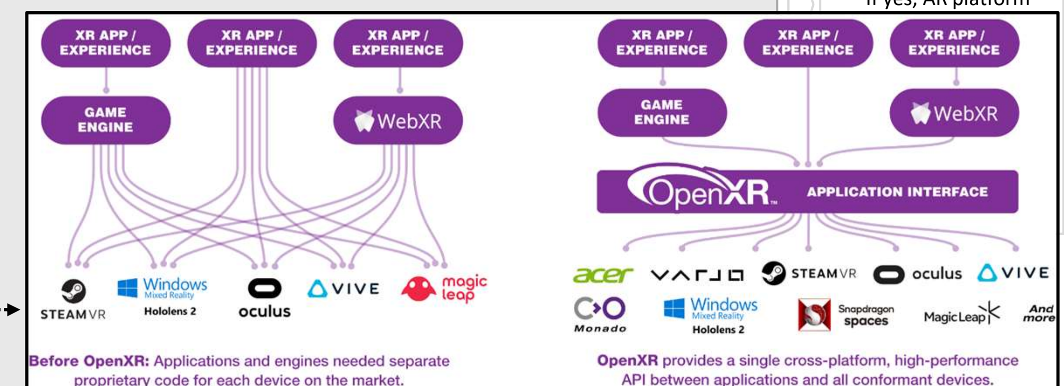
4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

Selection criteria:

1. Usage conditions-specific:
1. Lighting conditions
2. Network connectivity: offline mode support yes/ no
3. Noise
4-5. Temperature + humidity
6-7. Drop-safe + water/dust-proof
8. Health/ safety compliance
9. Hand usage
10. User interactions: hand, eye, headset tracking; voice commands
11. Movement restrictions: e.g., tethered AR headsets cause more restrictions than a phone/ tablet/ non-tethered AR headsets

2. Hardware-specific:
1-2. Battery life + device weight
3. Field-of-view
4-5. Camera + display resolution
6. Refresh rate
7-9. Storage + computation + remote rendering
10. Cross-device development
11. App download required
12. Heat distribution
13. Cost: hardware + subscription



DISCOVERY*

Produces ARIF's inputs:

- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AGILE*:

DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:

- Validation if AR is suitable for target use cases
- If yes, AR platform

*** Supplemented with Definition Tables + Decision Matrices* *Photo credit:* https://www.khronos.org/openxr/

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION FRAMEWORK: GUIDING AR USE CASE ASSESSMENT

ACTIVITY	Assess process suitability for AR	Assess AR platform suitability**: WebAR vs. Native AR vs. AR-on-headset	Assess AR dev. tool suitability**: Tracking + Rendering Engine	Refine process requirements
ACTIVITY GUIDANCE	**Characteristics which make a process ideal for AR:** **1. Location-based context** E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine **2. Hard-to-simulate environment** E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping **3. Hands-free access to content** E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox **4. Remote assist** E.g., Remote workers visually guide and collaborate with local workers without geographical constraints. **5. Navigation** E.g., AR-guided emergency & rescue	**Selection criteria:** **1. Usage conditions-specific:** 1. Lighting conditions 2. Network connectivity: offline mode support yes/ no 3. Noise 4-5. Temperature + humidity 6-7. Drop-safe + water/dust-proof 8. Health/ safety compliance 9. Hand usage 10. User interactions: hand, eye, headset tracking; voice commands 11. Movement restrictions: e.g., tethered AR headsets cause more restrictions than a phone/ tablet/ non-tethered AR headsets **2. Hardware-specific:** 1-2. Battery life + device weight 3. Field-of-view 4-5. Camera + display resolution 6. Refresh rate 7-9. Storage + computation + remote rendering 10. Cross-device development 11. App download required 12. Heat distribution 13. Cost: hardware + subscription	**Tracking and rendering engines are benchmarked using the following criteria.** **1. Tracking capabilities: Different use cases require different tracking capabilities** 1-2. Fiducial + image tracking 3. Object tracking 4. Face tracking 5. Location tracking 6. Surface tracking 7. Spatial tracking 8. Other tracking techniques 9. Multi-marker tracking 10. Multi-user AR session 11. Depth tracking 12. Light effects **2. Rendering capabilities: Rendering speed is affected by network connection + rendering engine's design + hardware capabilities, and therefore not assessed here.** 1. Light estimation: more realistic rendering 2. Occlusion: more realistic rendering **3. Ease of development:** 1. Integration with other AR dev. tools: checks which tracking engine integrates with which rendering engine 2. Simulation/ remote testing: 3. No-code/ low-code development **4. Licensing cost** 1. Open-source: yes/ no	**Activities:** **1. Refine process requirements collected from Discovery phase** > Functional requirements are captured as user stories > Non-functional requirements are used as part of acceptance criteria for relevant user stories

*** Supplemented with Definition Tables + Decision Matrices*

AGILE*:
DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

AR Implementation Framework

DISCOVERY*

Produces ARIF's inputs:
- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION METHODOLOGY: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

Assess process suitability for AR

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

Assess AR platform suitability**:
WebAR vs. Native AR vs. AR-on-headset

Selection criteria:

1. Usage conditions-specific:
1. Lighting conditions
2. Network connectivity: offline mode support yes/ no
3. Noise
4-5. Temperature + humidity
6-7. Drop-safe + water/dust-proof
8. Health/ safety compliance
9. Hand usage
10. User interactions: hand, eye, headset tracking; voice commands
11. Movement restrictions: e.g., tethered AR headsets cause more restrictions than a phone/ tablet/ non-tethered AR headsets

2. Hardware-specific:
1-2. Battery life + device weight
3. Field-of-view
4-5. Camera + display resolution
6. Refresh rate
7-9. Storage + computation + remote rendering
10. Cross-device development
11. App download required
12. Heat distribution
13. Cost: hardware + subscription

Assess AR dev. tool suitability**: Tracking + Rendering Engine

Tracking and rendering engines are benchmarked using the following criteria.

1. Tracking capabilities: Different use cases require different tracking capabilities
1-2. Fiducial + image tracking
3. Object tracking
4. Face tracking
5. Location tracking
6. Surface tracking
7. Spatial tracking
8. Other tracking techniques
9. Multi-marker tracking
10. Multi-user AR session
11. Depth tracking
12. Light effects

2. Rendering capabilities: Rendering speed is affected by network connection + rendering engine's design + hardware capabilities, and therefore not assessed here.
1. Light estimation: more realistic rendering
2. Occlusion: more realistic rendering

3. Ease of development:
1. Integration with other AR dev. tools: checks which tracking engine integrates with which rendering engine
2. Simulation/ remote testing:
3. No-code/ low-code development

4. Licensing cost
1. Open-source: yes/ no

Refine process requirements

Activities:
1. Refine process requirements collected from Discovery phase
> Functional requirements are captured as user stories
> Non-functional requirements are used as part of acceptance criteria for relevant user stories

*** Supplemented with Definition Tables + Decision Matrices*

AGILE*:
DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:
- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

Key Takeaways

AR by itself = cool…

But AR when combined with the right technologies (IoT, AI, etc.) for the right use cases = superpower.

First times are beautiful. So are second's and third's.

AR as uncharted territory.
Transitioning from GCP to AWS.
First time setting up CI/CD + IaC templates.
There are always better ways to do things.

Appendix: Definition Table of Characteristics of Ideal Process for AR

#	Process Characteristic	Definition
1	Location-based context	A process is ideal for AR when worker productivity is improved when provided location-based context i.e., (real-time) information as anchored to a physical object or environment. For example, a shopfloor manager can view an AR dashboard with real-time sensor data as anchored to a physical equipment to quickly inspect the current status of the equipment. Another example is an AR-guided work instructions anchored to a physical machine which allows workers to approach the machine and access the work instructions on demand as the worker carry out a complex task (video).
2	Hard-to-simulate environment	A process is ideal for AR when worker productivity is improved when allowed to interact with AR contents which are hard to be simulated otherwise in real life. For example, instead of relying on 2D medical scan images, surgeons can view a 3D model of a patient anatomy for pre-surgical planning. In this case, patient anatomy is considered a hard-to-simulate environment. Additional examples are AR-enabled product prototyping (experimenting with different design before actual product fabrication), 3D mesh of a crime scene (video), construction planning (video), layout planning (video), and bridge inspection (video).
3	Hands-free access to content	A process is ideal for AR when worker productivity is improved when provided access to content without having to use their hands. For example, surgeons can view patient's medical records during surgeries using voice commands (video).
4	Remote assist	A process is ideal for AR when worker productivity is improved when remote workers can guide and collaborate without geographical constraints. For example, through live camera streaming, a remote worker can share the same view as the local worker and makes live, virtual annotations on the view to guide the local worker through a task (video).
5	Navigation	A process is ideal when worker productivity is improved when guided to a target destination by virtual AR contents. For example, a traveler can be guided to their gate at an unfamiliar airport by following virtual arrows for directions (photo).

Appendix: Definition Table of AR Platform Selection Criteria 1/2

#	Category	Selection Criteria	Definition
1	Usage conditions-specific	Lighting conditions	Harsh lighting conditions (too dim or too bright) will require AR platforms whose tracking engine must be robust enough to process live camera feed of degrading quality and detect a marker.
2		Network connectivity	When deployed in environments without stable internet connection like shopfloors, ideal AR platforms are the ones with offline mode support.
3		Noise	When deployed in loud environments like shopfloors, ideal AR platforms are those with noise-cancelling microphones.
4-7		Temperature + Humidity + Drop-safe + Water/dust-proof	When deployed in rugged conditions, ideal AR platforms are those built for extreme temperature, humidity, drop-safe, waterproof, and dustproof.
8		Health/ safety compliance	Some use cases will require AR platforms to comply with specific health and safety standards e.g., hardhat integration, medical certifications for clean room usage, eye safety.
9		Hand usage	Some tasks require users to use both of their hands e.g., surgeons carrying out a surgery (making AR headsets most ideal) while some tasks occupy only one hand, allowing users to use their other hand to hold a mobile device (making it possible to use webAR or native AR).
10		10. User interactions	Different AR platforms support different built-in user interactions e.g., voice/ gesture/ gaze controls for an intuitive and enhanced user experience.
11		11. Movement restrictions	Some tasks require users to have a full range of movement (e.g., shopfloor operators), making non-tethered AR headsets, webAR, and native AR ideal options. Some other tasks require only a limited range of movements, making tethered AR headsets an acceptable option in exchange for better tracking and rendering performance and lower latency since the tethered headset usually is connected to a powerful computer.

Appendix: Definition Table of AR Platform Selection Criteria 2/2

#	Category	Selection Criteria	Definition
1	Hardware-specific	Battery life	The longer the battery life, the fewer charges are required between usage.
2		Device weight	The heavier the device, the more fatigue it causes, especially head fatigue when using AR headsets.
3		Field-of-view (FoV)	The wider the FoV, the bigger virtual contents users can view and the more immersive the AR experience feels. For virtual product prototyping, a big FOV is preferable while for other use cases such as an AR monitoring dashboard for factory equipment, an average sized FoV might be acceptable.
4		Camera resolution	The higher the camera resolution, the higher quality video the camera can capture. It is valuable, for example, when the live camera is streamed to a remote worker for the use case of AR-guided remote assistance.
5		Display resolution	The higher the display resolution, the higher fidelity the virtual contents are.
6		Refresh rate	The higher refresh rate, the smoother the virtual contents appear.
7-9		Storage + computation + remote rendering	Storage, computation, and remote rendering dictate how much tracking and rendering can be performed locally on the AR device (no latency) or remotely in the cloud (requiring less powerful AR devices but results in higher latency).
10		Cross-device development	Allows developers to develop a WebAR, native AR, and AR-on-headset application once and deploy the application on multiple browsers, Android/ iOS devices, and AR headsets, respectively.
11		App download required	Refers to if a user needs to download and install the AR app to their device. WebAR is the only platform that does not require users to download and install WebAR apps since WebAR runs directly from a browser, giving it an advantage over native AR and AR headsets.
12		Heat distribution	Refers to how much heat an AR device produces while running and how fast the heat can dissipate because of the thermal model of the AR device. This factor is important because heating AR devices, especially AR headsets, can cause skin burns and affect user experience.
13		Cost: hardware + subscription	Refers to the cost of using the AR platforms (hardware cost + subscription cost).

Appendix: Definition Table of AR Dev. Tool Selection Criteria 1/2

#	Category	Selection Criteria	Definition
1-7	Tracking capabilities	Fiducial tracking; Image tracking; Face tracking; Location tracking; Object tracking; Surface tracking; Spatial tracking	Different use cases require different tracking techniques. In the example of an art book in here, the art book is implemented using an image tracking engine which allows users to scan an image of a sculpture in the artbook and view a 3D model of the sculpture rendered on top of the image. On the other hand, spatial tracking is more appropriate for implementing, say, an AR-guided evacuation route for an underground mine since it would not be feasible to attach image markers to rock faces and make sure the image markers stay put.
8		Depth tracking	Depth tracking is an additional capability of tracking engines to understand the physical environment. With depth knowledge, tracking engines can instruct rendering engines to occlude virtual objects if they are behind physical objects for a more realistic experience.
9		Other tracking	As more computer vision technology evolves, more tracking techniques are being developed. This criterion serves as a catch-all for those techniques.
10		Multi-marker tracking	Refers to a capability of tracking engines to detect and track multiple markers in a single video frame, creating a richer experience (picture).
11		Multi-user tracking	Refers to the ability of tracking engines to synchronize across multiple devices and allow multiple users to join a single AR session. For example, an AR-guided remote assistance solution requires the use of multi-user tracking (video).
12		Lighting effects	Refers to additional capabilities of tracking engines such as light estimate i.e., predicting the lighting conditions of the physical environment (picture).

Appendix: Definition Table of AR Dev. Tool Selection Criteria 2/2

#	Category	Selection Criteria	Definition
1	Rendering capabilities	Light estimates	Using the light estimate data from tracking engines, rendering engines can shade the virtual contents to match the lighting conditions of the physical environment for more realistic virtual contents (picture).
2		Occlusion	Using the depth data from tracking engines, rendering engines can occlude virtual objects which stand behind physical objects for more realistic virtual contents (picture).
1	Ease of develop-ment	Integration with other AR development tools	Cross-references which tracking engines integrate with which rendering engines. Refresher: an AR application requires both tracking and rendering engines, and the two engines need to integrate with each other.
2		Simulation/ remote testing	Allows developers to test and debug AR applications more quickly.
3		Low-code/ no-code development	Allows business users with little to no programming knowledge to create new AR experiences e.g., allowing shopfloor operators to create new AR-guided work instructions.
1	Licensing cost	Open-source	Checks if the tracking/ rendering engines are open-source or not.

Appendix: AR Platform Suitability Decision Matrix 1/4

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by: 1) Usage condition-specific 2) Hardware

	Selection Criteria	WebAR (web browser)	Native AR (Android, iOS)	Varjo XR-3 (2020)	HoloLens 2 (2019)	Magic Leap 2 (2022)	Meta Quest Pro (2022)	Vuzix Blade 2 (2022)	Vuzix M400 (2020)	Google Glass 2 (2019)
1. Usage conditions-specific selection criteria	1. Lighting conditions	Irrespective of AR platforms, their tracking engine performs better or worse in different light conditions due to the fluctuating quality of video frames being captured in different light conditions, making it easy or hard for the tracking engine's computer vision algorithms to detect a marker in those video frames. In order to choose an AR platform that best accommodates the target lighting conditions: 1) Test different candidate AR platforms in different lighting conditions and choose the most performant one 2) Or: customize the tracking engine's computer vision algorithms 3) Or: customize the camera's properties to improve the quality of the captured video frames e.g., reduce the camera's exposure level in an overly bright environment (source)								
	2. Network connectivity	Offline mode supported when implementing Service Worker	Offline mode supported	Offline mode supported with offline subscription	Work instructions in Dynamics 365 Guides support offline mode with limitations (e.g., no video calls)	No info about offline mode support	No info about offline mode support	Offline mode supported	Offline mode supported	No info about offline mode support
	3. Noise	Device-specific	Device-specific	No info	5 noise cancelling microphones	No info	No info	2 noise-cancelling microphones	3 noise-cancelling microphones	3 noise cancelling microphones
	4. Operating temperature	Device-specific	Device-specific	No info	10°C to 35°C	10°C to 30°C	No info	0°C to 35°C	-20°C to 45°C	0°C to 35°C
	5. Operating humidity	Device-specific	Device-specific	No info	No info	No info	No info	0% to 95%	0% to 95%	5% to 95%
	6. Drop-safe	Device-specific	Device-specific	No info	No info	No info	No info	No info	MIL-STD-810G certification	No info
	7. Water/ Dustproof	Device-specific	Device-specific	No info	IP50 Dust proof	No info	No info	No info	IP67 Dust + water protection certification	IP53 (Resistant to water spray and limited dust ingression)

Appendix: AR Platform Suitability Decision Matrix 2/4

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by: 1) Usage condition-specific 2) Hardware

	Selection Criteria	WebAR (web browser)	Native AR (Android, iOS)	Varjo XR-3 (2020)	HoloLens 2 (2019)	Magic Leap 2 (2022)	Meta Quest Pro (2022)	Vuzix Blade 2 (2022)	Vuzix M400 (2020)	Google Glass 2 (2019)
1. Usage conditions-specific selection criteria	8. Compliance with health/ safety standards	Device-specific	Device-specific	No info	• ANSI Z87.1, CSA Z94.3 and EN 166 certifications for eye safety. • Hardhat-integrated; • Compliant with regulated environments e.g., clean rooms;	IEC 60601 certifications for medical use	No info	• UV protection lens; • ANSI Z87.1 for eye safety.;	• IEC 60601 certifications for medical use • Comes with hardhat mount;	No info
	9. Hand usage	One hand occupied to hold mobile device.		Hands-free	Hands-free	Hands-free with one hand-held controller	Hands-free with two hand-held controllers	Hands-free	Hands-free	Hands-free
	10. User interactions	Hand tracking possible when implementing hand tracking engines like Ultraleap and Handtrack.js; Voice commands are possible using speech recognition APIs like Web Speech API (for web AR) or Cordova Speech Recognition API (native AR Android/ iOS);		Eye tracking; Headset and controller tracking;	Voice command; Eye tracking; Headset tracking; Hand tracking;	Eye tracking; Hand tracking; Voice commands; Controller tracking	Eye tracking; Controller tracking; Hand tracking;	Touchpad gestures; Voice control;	Voice control;	Touchpad gestures; voice commands;
	11. Movement restrictions	Non-tethered		Tethered	Non-tethered	Non-tethered but comes with a wired, pocket-size external processor called Compute Pack	Non-tethered	Non-tethered	Non-tethered	Non-tethered

Appendix: AR Platform Suitability Decision Matrix 3/4

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by: 1) Usage condition-specific 2) Hardware

	Selection Criteria	WebAR (web browser)	Native AR (Android, iOS)	Varjo XR-3 (2020)	HoloLens 2 (2019)	Magic Leap 2 (2022)	Meta Quest Pro (2022)	Vuzix Blade 2 (2022)	Vuzix M400 (2020)	Google Glass 2 (2019)
2. Hardware-specific selection criteria	1. Battery life	Device-specific	Device-specific	No info	2-3 hours	3.5 hours	1-2 hours	No info	2 hours with external battery possible	8 hours
	2. Device weight	Device-specific	Device-specific	594 g + headband 386 g	566 g	260 g	722 g	No info	182 g	51 g
	3. Field of view (horizontal)	N/A		115°	43°	70°	106°	20°	16.8°	83°
	4. Camera resolution	Device-specific	Device-specific	12 MP	8 MP	12.6 MP	No info	8 MP	12.8 MP	8 MP
	5. Display resolution (per eye)	Device-specific	Device-specific	Focus area (27° x 27°) at 1920 x 1920 pixel; Peripheral area at 2880 x 2720 pixel;	1440 x 936 pixel	1440 x 1760 pixel	1800 x 1920 pixel	480 x 480 pixel	854 x 480 pixel	640 x 360 pixel
	6. Refresh rate	Depending on the tracking and rendering engine		90 Hz	60 Hz	120 Hz	90 Hz	No info	No info	No info
	7. Storage capacity	Device-specific	Device-specific	No info	4GB RAM; 64GB storage;	16GB RAM; 256GB storage;	12GB RAM; 256GB storage;	40GB storage	6GB RAM; 64GB storage	3GB RAM; 32GB storage
	8. Computation capacity	Device-specific	Device-specific	No info	CPU: Octa-core Kryo 385; GPU: Adreno 630	CPU: AMD 7nm Quad-core Zen2 X86 core; GPU: AMD GFX10.2	CPU: Octa-core Kryo 585; GPU: Adreno 650	CPU: Quad Core ARM	CPU: 8 Core 2.52Ghz Qualcomm XR1	CPU: Octa-core Kryo; GPU: Adreno 615
	9. Remote rendering	No native integration	No native integration	Yes – Varjo Reality Cloud	Yes – Azure Remote rendering	Yes – Integrates with NVIDIA CloudXR	No info	No info	No info	No info

Appendix: AR Platform Suitability Decision Matrix 4/4

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by: 1) Usage condition-specific 2) Hardware

	Selection Criteria	Selection criteria description	WebAR (web browser)	Native AR (Android, iOS)	Varjo XR-3 (2020)	HoloLens 2 (2019)	Magic Leap 2 (2022)	Meta Quest Pro (2022)	Vuzix Blade 2 (2022)	Vuzix M400 (2020)	Google Glass 2 (2019)
2. Hardware-specific selection criteria	10. Cross-device develop-ment	Allows developers to develop a webAR, native AR, and AR-on-headset application once and deploy the application on multiple browsers, Android/ iOS devices, and AR headsets, respectively.	Likely – Most webAR tracking and rendering engines are built upon browser's natively supported features such as WebGL – see example of browser requirements for 8th Wall tracking engine	Likely – Some tracking engines like Vuforia support build for both Android and iOS. ARCore only supports Android. ARKit only supports iOS – see AR Development Tool Decision Matrix for details	Yes – integrates with OpenXR*;	Yes – integrates with OpenXR;	Yes – integrates with OpenXR;	No info	No integration with OpenXR (yet)	No integration with OpenXR (yet)	No integration with OpenXR (yet)
	11. App download required	Refers to if a user needs to download and install the AR app to their device.	No	Yes							
	12. Heat distribution	Refers to how much heat an AR device produces while running and how fast the heat dissipates according to the thermal design of the AR device. Note heating AR devices, especially AR headsets, can cause skin burns and affect user experience.	It appears that there is no standard measure for benchmarking the thermal model of different AR devices. Heat distribution is primarily a hardware problem with the chips being one of the main heat-generating components (source). Therefore, it is recommended to experiment with different AR devices for the target usage conditions and select the most comfortable headset.								
	13. Cost	Refers to the cost of using the AR platforms.	Device-specific	Device-specific	€6.495 + mandatory XR Subscription	€ 3.849,00+ + optional HoloLens subscription	~€3,167+ ($3.299+)	€1.799,99	€1,669.80	€2.311,10	~€1,090 ($1,144)

LIQUID STUDIO.NL BE DIFFERENT

UNIVERSITY OF TWENTE. accenture

Appendix: AR Dev. Tool Suitability Decision Matrix 1/3

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by:
1) Tracking capabilities 2) Rendering capabilities 3) Ease of development 4) Licensing cost

Tracking engine	Rendering engine	Tracking + Rendering

	Selection Criteria (SC)	MindAR	AR.js	WebXR	8th Wall	Lightship ARDK (2021)	Vuforia (2011)	Azure Spatial Anchors	ARCore (2018)	ARKit (2017)	Manifest (2017)	Three.js	A-frame	Unity	Unreal	RealityKit	Adobe Aero (2019)	Meta Spark Studio (2017)
	AR platforms supported	WebAR	WebAR	WebAR	WebAR	Native AR (Android, iOS)	Native AR, AR headset (HoloLens 2, Magic Leap 2, Vuzix, RealWear)	Native AR (Android, iOS), AR headset (HoloLens)	Native AR (Android)	Native AR (iOS)	Native AR, AR headset (HoloLens, Magic Leap, Realwear)	WebAR	WebAR	Native AR, AR headset	Native AR, AR headset	Native AR (iOS)	WebAR (Aero URL); Native AR (Android, iOS)	Native AR (Android, iOS), AR headset (Meta Quest Pro)
1. Tracking capabilities	1. Fiducial tracking		X				X (VuMark)				No info	N/A	N/A	N/A	N/A	N/A		
	2. Image tracking	X	X	X	X	X	X (Image, cylinder, multi targets)		X	X	No info	N/A	N/A	N/A	N/A	N/A	X (Image anchor)	X (target tracking)
	3. Face tracking	X			X				X	X	No info	N/A	N/A	N/A	N/A	N/A		X
	4. Location tracking		X		X	X			X	X	No info	N/A	N/A	N/A	N/A	N/A		
	5. Object tracking						X (Model targets)			X (Physical objects)	No info	N/A	N/A	N/A	N/A	N/A		
	6. Surface tracking			X (Hit test)	X	X	X (Ground plane)		X (Hit test)	X (Surface detection)	No info	N/A	N/A	N/A	N/A	N/A	X (Surface anchor)	X (plane tracking)

Appendix: AR Dev. Tool Suitability Decision Matrix 2/3

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by:
1) Tracking capabilities 2) Rendering capabilities 3) Ease of development 4) Licensing cost

Tracking engine	Rendering engine	Tracking + Rendering

	Selection Criteria (SC)	MindAR	AR.js	WebXR	8th Wall	Lightship ARDK (2021)	Vuforia (2011)	Azure Spatial Anchors	ARCore (2018)	ARKit (2017)	Manifest (2017)	Three.js	A-frame	Unity	Unreal	RealityKit	Adobe Aero (2019)	Meta Spark Studio (2017)
1. Tracking capabilities	7. Spatial tracking					X	X (Area targets)	X (Spatial anchors)			No info	N/A	N/A	N/A	N/A	N/A		
	8. Other tracking									Body tracking;	No info	N/A	N/A	N/A	N/A	N/A		Iris tracking; body tracking; Hand tracking;
	9. Multi-marker tracking	X	X		X (image tracking)		X		X (image tracking)	X (image tracking)	No info	N/A	N/A	N/A	N/A	N/A		X (image tracking; plane tracking)
	10. Multi-user AR session			Possible with tools like Wrapper.js		X	X (Vuforia Chalk remote assist)	X	X (Cloud anchors)	X	No info	N/A	N/A	N/A	N/A	N/A		
	11. Depth tracking			X		X			X	X	No info	N/A	N/A	N/A	N/A	N/A		
	12. Lighting effects			Light estimate;	Light estimate ;	Light estimate;				Light estimate ; realistic reflection;	No info	N/A	N/A	N/A	N/A	N/A		

Appendix: AR Dev. Tool Suitability Decision Matrix 3/3

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by:
1) Tracking capabilities 2) Rendering capabilities 3) Ease of development 4) Licensing cost

Tracking engine | Rendering engine | Tracking + Rendering

	Selection Criteria (SC)	MindAR	AR.js	WebXR	8th Wall	Lightship ARDK (2021)	Vuforia (2011)	Azure Spatial Anchors	ARCore (2018)	ARKit (2017)	Manifest (2017)	Three.js	A-frame	Unity	Unreal	RealityKit	Adobe Aero (2019)	Meta Spark Studio (2017)
2. Rendering engine	1. Light estimation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X (WebXR)	X (WebXR)	X (ARCore, ARKit)	X (ARCore; ARKit)	X (ARKit)		
	2. Occlusion	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			X (ARCore, ARKit)	X (ARCore;ARKit)	X (ARKit)		
3. Ease of develop-ment	1. Integration with other AR dev. tools	Three.js; A-frame;	Three.js; A-frame;	Three.js; A-frame;	Three.js; A-frame;	Unity;	MRTK; Magic Leap OS; ARCore/ ARKit;	Unity; ARCore;	Vuforia; Unity; Unreal; WebXR;	Vuforia; Unity; Unreal;	Unity;	WebXR;	WebXR;	OpenXR; MRTK; ARCore; ARKit;	OpenXR; MRTK; ARCore; ARKit;	ARKit		
	2. Simulation/ remote testing			X (WebXR API Emulator)		X (Mock mode)	X (Play mode)		X (Android emulator)		No info			X (AR Foundation Remote for ARCore+ARKit)	X (In-editor testing)			X (simulator)
	3. Low-code/ no-code development						X (Vuforia Chalk, Expert Capture, Instruct, Studio)				X (Manifest Maker)						X	X
4. Licensing cost	1. Open-source	X	X	X								X	X					

LIQUID STUDIO.NL BE DIFFERENT

UNIVERSITY OF TWENTE. accenture

Augmented Reality Implementation Methodology

Kristen Phan

MSc Business Information Technology

Supervisors:

UT: Prof. Dr. Maria E. Iacob, Dr-Ing. Florian W. Hahn

Accenture: Ilia Shakitko

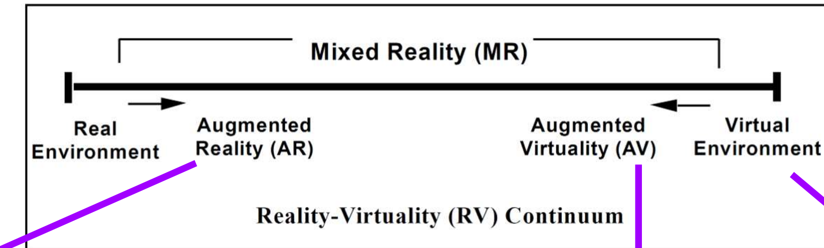
LIQUID STUDIO.NL BE DIFFERENT

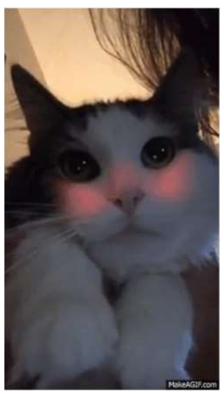
UNIVERSITY OF TWENTE. accenture

Agenda

1. Augmented Reality (AR) 101
2. Literature Review: Research Gaps + Research Questions
3. Artifact Design: ARIM
4. Artifact Demonstration: WebAR Prototype
5. Artifact Evaluation: Expert Interviews
6. Artifact Revision: Revised ARIM
7. Conclusion

Mixed Reality Spectrum





Source: P. Milgram, H. Takemura, A. Utsumi, and F. Kishino, "Augmented reality: A class of displays on the reality-virtuality continuum," in Telemanipulator and telepresence technologies, 1995, vol. 2351: Spie, pp. 282-292.
Photo credits:
https://gfycat.com/animatedmadbobcat
https://observer.com/2022/10/microsoft-teams-goes-virtual-and-avatars-finally-get-legs-as-mark-zuckerberg-announces-new-metaverse-developments/
https://www.rtlnieuws.nl/tech/artikel/5264551/microsoft-stort-zich-op-metaverse-teams-krijgt-live-3d-avatars

How Does AR Work?

Two technologies underpin AR:

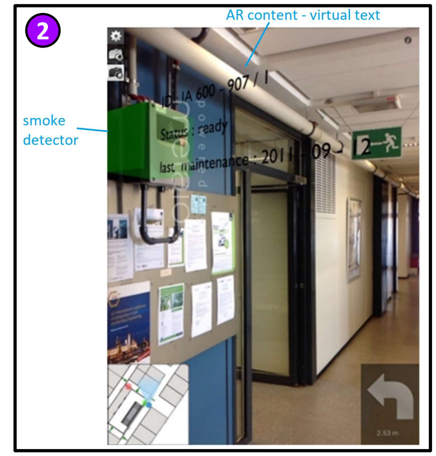
- *Tracking engine = Tracking the location + orientation of a physical object/ environment from live camera feed.*
- *Rendering engine = Displaying a virtual object as anchored to the physical object/ environment*

Common tracking techniques:

1. Fiducial/ image marker: 2D images
2. Object: 3D objects
3. Face: Snapchat filters
4. Location
5. Surface: planar surface
6. Spatial: 3D mesh of an environment
7. Others: Depth, hand, eye, body, head, controller tracking

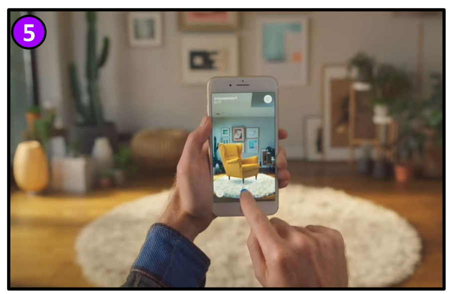
1

2



4

5



https://www.ikea.com/au/en/customer-service/mobile-apps/say-hej-to-ikea-place-pub1f8af050

6

AR 101 | Literature Review | Artifact Design | Artifact Demonstration | Artifact Evaluation | Artifact Revision | Conclusion

AR Platforms: Native AR v. WebAR v. AR Headset

Each platform has its own capabilities and limitations.

Native AR + WebAR

> Native AR apps: Downloaded to and installed on user device.
> WebAR apps: Run directly from web browser; Sharable through an URL.

A virtual recipe book rendered on the physical label of a Heinz ketchup bottle.

AR Headset

> Requires dedicated hardware: HoloLens, Magic Leap, etc.
> Has built-in tracking capabilities (hand, eye, head, hand-held controller tracking) + can integrate external tracking engine.

Colleagues collaborate remotely via video call on a HoloLens headset.

Source: https://www.blippar.com/ar-studio; https://dynamics.microsoft.com/en-gb/mixed-reality/remote-assist/

AR Platforms: Native AR v. WebAR v. AR Headset

Each platform has its own capabilities and limitations.

Native AR + WebAR

> Native AR apps: Downloaded to and installed on user device.
> WebAR apps: Run directly from web browser; Sharable through an URL.

A virtual recipe book rendered on the physical label of a Heinz ketchup bottle.

AR Headset

> Requires dedicated hardware: HoloLens, Magic Leap, etc.
> Has built-in tracking capabilities (hand, eye, head, hand-held controller tracking) + can integrate external tracking engine.

Colleagues collaborate remotely via video call on a HoloLens headset.

Source: https://www.blippar.com/ar-studio; https://dynamics.microsoft.com/en-gb/mixed-reality/remote-assist/

AR Platforms: Native AR v. WebAR v. AR Headset

Each platform has its own capabilities and limitations.

Native AR + WebAR

> Native AR apps: Downloaded to and installed on user device.
> WebAR apps: Run directly from web browser; Sharable through an URL.

A virtual recipe book rendered on the physical label of a Heinz ketchup bottle.

AR Headset

> Requires dedicated hardware: HoloLens, Magic Leap, etc.
> Has built-in tracking capabilities (hand, eye, head, hand-held controller tracking) + can integrate external tracking engine.

Colleagues collaborate remotely via video call on a HoloLens headset.

Existing Literature on AR Implementation Methodology

Three papers were selected.

Paper: Strategies for the successful implementation of augmented reality (Berman et al.)

Paper: Evaluating human factors in augmented reality systems (Livingston.)

Paper: A Review and Implementation Framework of Industrial Augmented Reality (Mühlan et al.)

Existing Literature on AR Implementation Methodology

Three papers were selected.

Paper: Strategies for the successful implementation of augmented reality (Berman et al.)

Paper: Evaluating human factors in augmented reality systems (Livingston.)

Paper: A Review and Implementation Framework of Industrial Augmented Reality (Mühlan et al.)

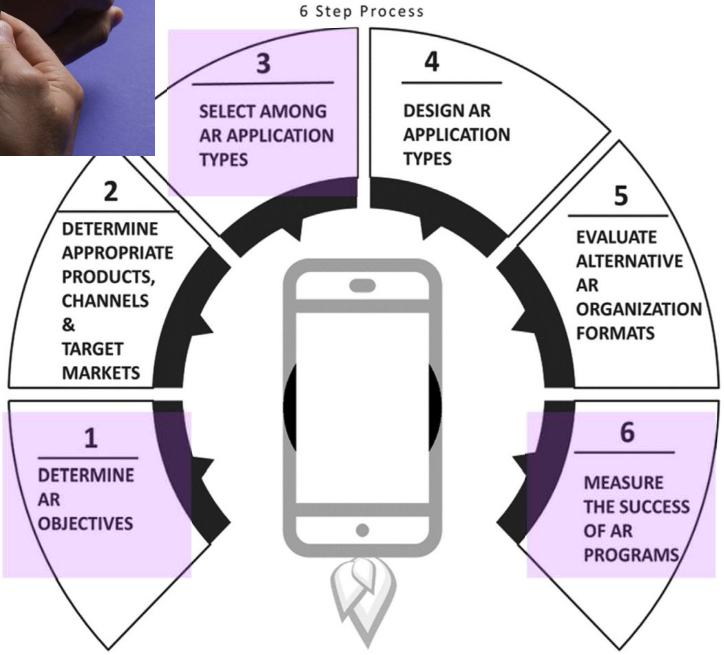


Photo credit: https://www.drip.com/blog/virtual-try-on-examples

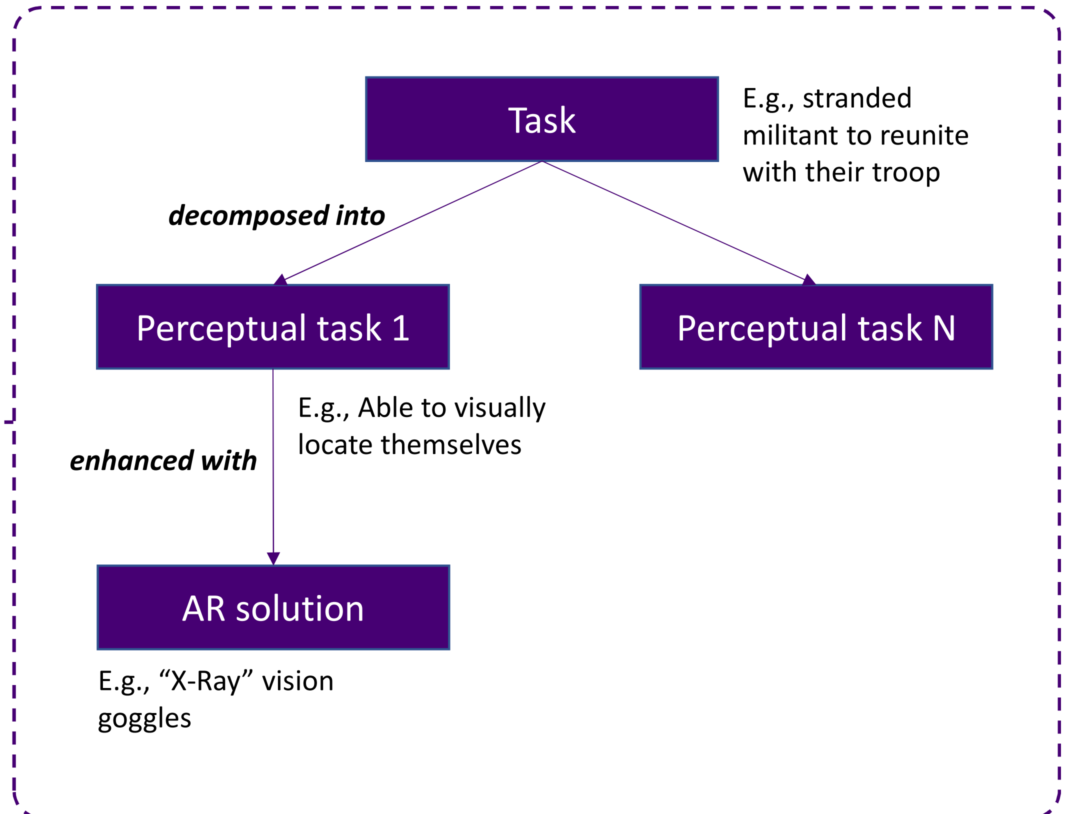
Existing Literature on AR Implementation Methodology

Three papers were selected.

Paper: Strategies for the successful implementation of augmented reality (Berman et al.)

Paper: Evaluating human factors in augmented reality systems (Livingston.)

Paper: A Review and Implementation Framework of Industrial Augmented Reality (Mühlan et al.)



AR 101 | **Literature Review** | Artifact Design | Artifact Demonstration | Artifact Evaluation | Artifact Revision | Conclusion

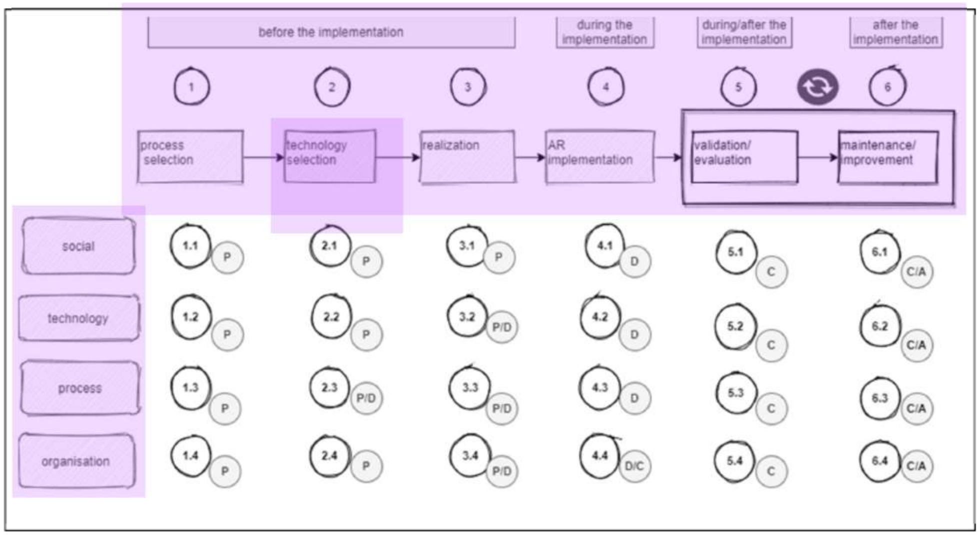
Existing Literature on AR Implementation Methodology

Three papers were selected.

Paper: Strategies for the successful implementation of augmented reality (Berman et al.)

Paper: Evaluating human factors in augmented reality systems (Livingston.)

Paper: A Review and Implementation Framework of Industrial Augmented Reality (Mühlan et al.)



Key Research Gaps from Existing Literature

Translated to Research Questions.

PROCESS SUITABILITY FOR AR

Can a business process be enhanced with the use of AR?

AR PLATFORM SUITABILITY

Which AR platform (WebAR v. native AR v. AR headset) is most suitable for the process?

AR DEV. TOOL SUITABILITY

Which tracking + rendering engines are suitable for the select process and AR platform?

Key Research Gaps from Existing Literature

Translated to Research Questions.

PROCESS SUITABILITY FOR AR

Can a business process be enhanced with the use of AR?

AR PLATFORM SUITABILITY

Which AR platform (WebAR v. native AR v. AR headset) is most suitable for the process?

AR DEV. TOOL SUITABILITY

Which tracking + rendering engines are suitable for the select process and AR platform?

Key Research Gaps from Existing Literature

Translated to Research Questions.

PROCESS SUITABILITY FOR AR

Can a business process be enhanced with the use of AR?

AR PLATFORM SUITABILITY

Which AR platform (WebAR v. native AR v. AR headset) is most suitable for the select process?

AR DEV. TOOL SUITABILITY

Which tracking + rendering engines are suitable for the select process and AR platform?

Key Research Gaps from Existing Literature

Translated to Research Questions.

PROCESS SUITABILITY FOR AR

Can a business process be enhanced with the use of AR?

AR PLATFORM SUITABILITY

Which AR platform (WebAR v. native AR v. AR headset) is most suitable for the process?

AR DEV. TOOL SUITABILITY

Which tracking + rendering engines are suitable for the select process and AR platform?

Research Question:

What does an industry-agnostic, tool-agnostic AR Implementation Methodology look like?

- What makes a process a good candidate for AR?
- How to choose between AR platform?
- How to choose between AR development tools (tracking + rendering engines)?

Key Inputs for the Proposed ARIM

Software Development Lifecycle	Design Thinking	Success Factors for AR Adoption

Key Inputs for the Proposed ARIM

Software Development Lifecycle

Design Thinking

Success Factors for AR Adoption

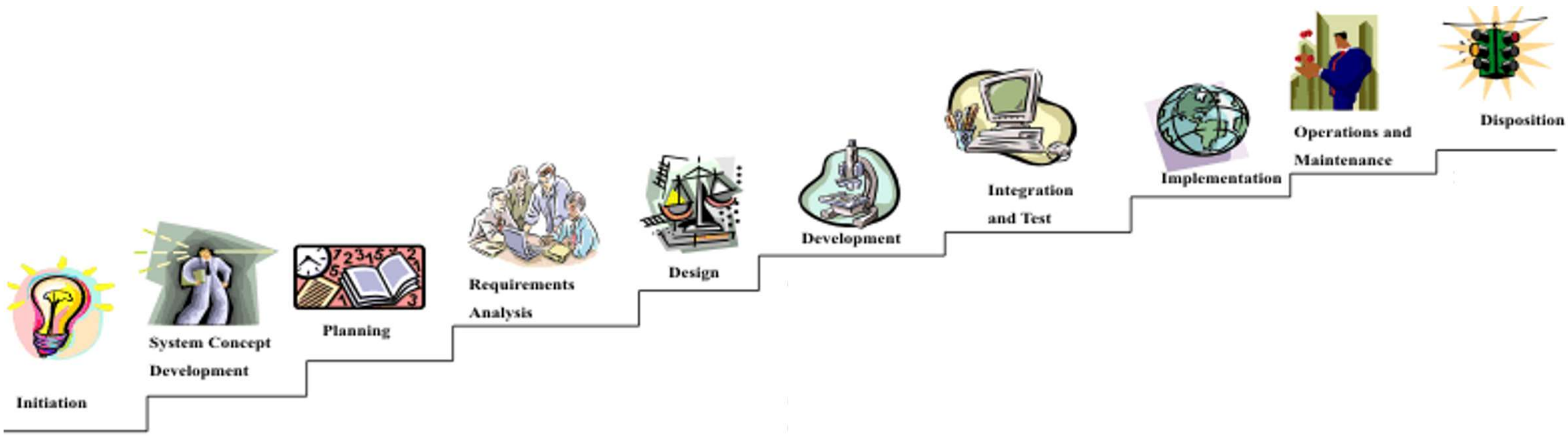


Photo credit: https://www.justice.gov/archive/jmd/irm/lifecycle/ch1.htm#para1.2

Key Inputs for the Proposed ARIM

Software Development Lifecycle

Design Thinking

Success Factors for AR Adoption

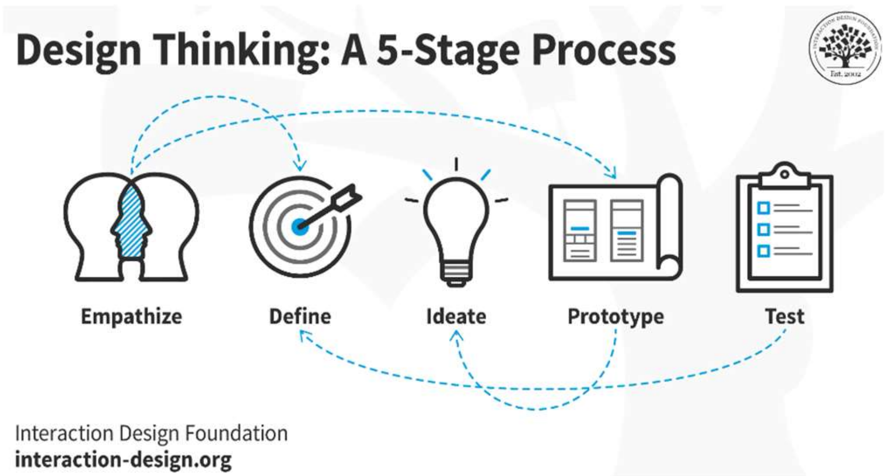


Photo credit: https://www.interaction-design.org/literature/topics/design-thinking

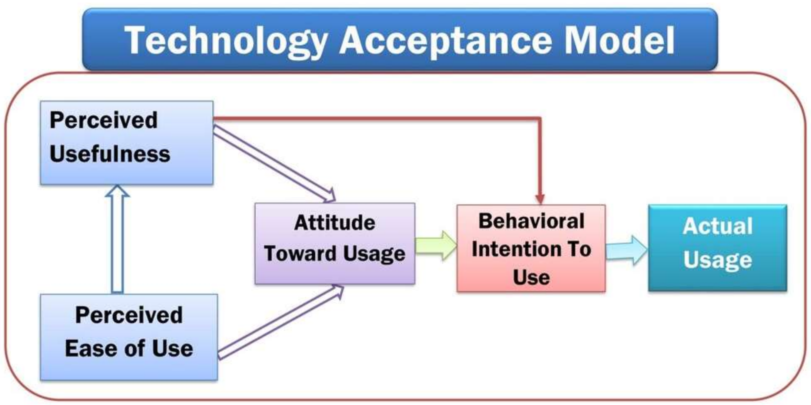
AR 101 | Literature Review | Artifact Design | Artifact Demonstration | Artifact Evaluation | Artifact Revision | Conclusion

Key Inputs for the Proposed ARIM

Software Development Lifecycle

Design Thinking

Success Factors for AR Adoption



Technology Acceptance Model (TAM) By Davis (1989)

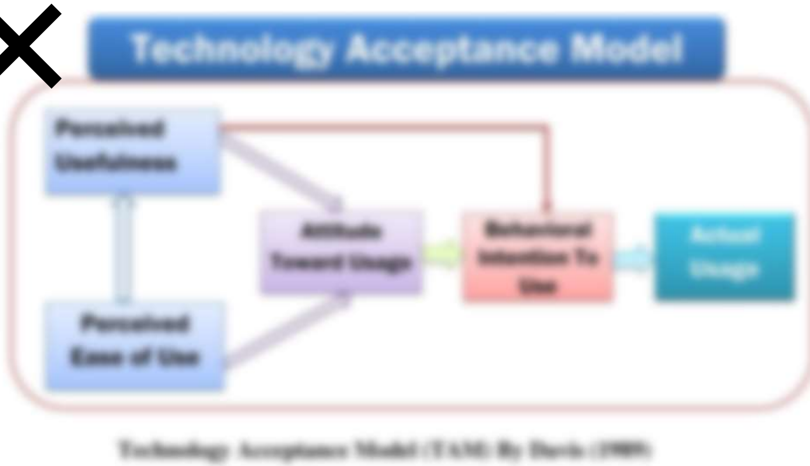
Photo credit: https://globalassistant.info/technology-acceptance-model-davis-1989-pdf-download-link-free/

Key Inputs for the Proposed ARIM

Software Development Lifecycle

Design Thinking

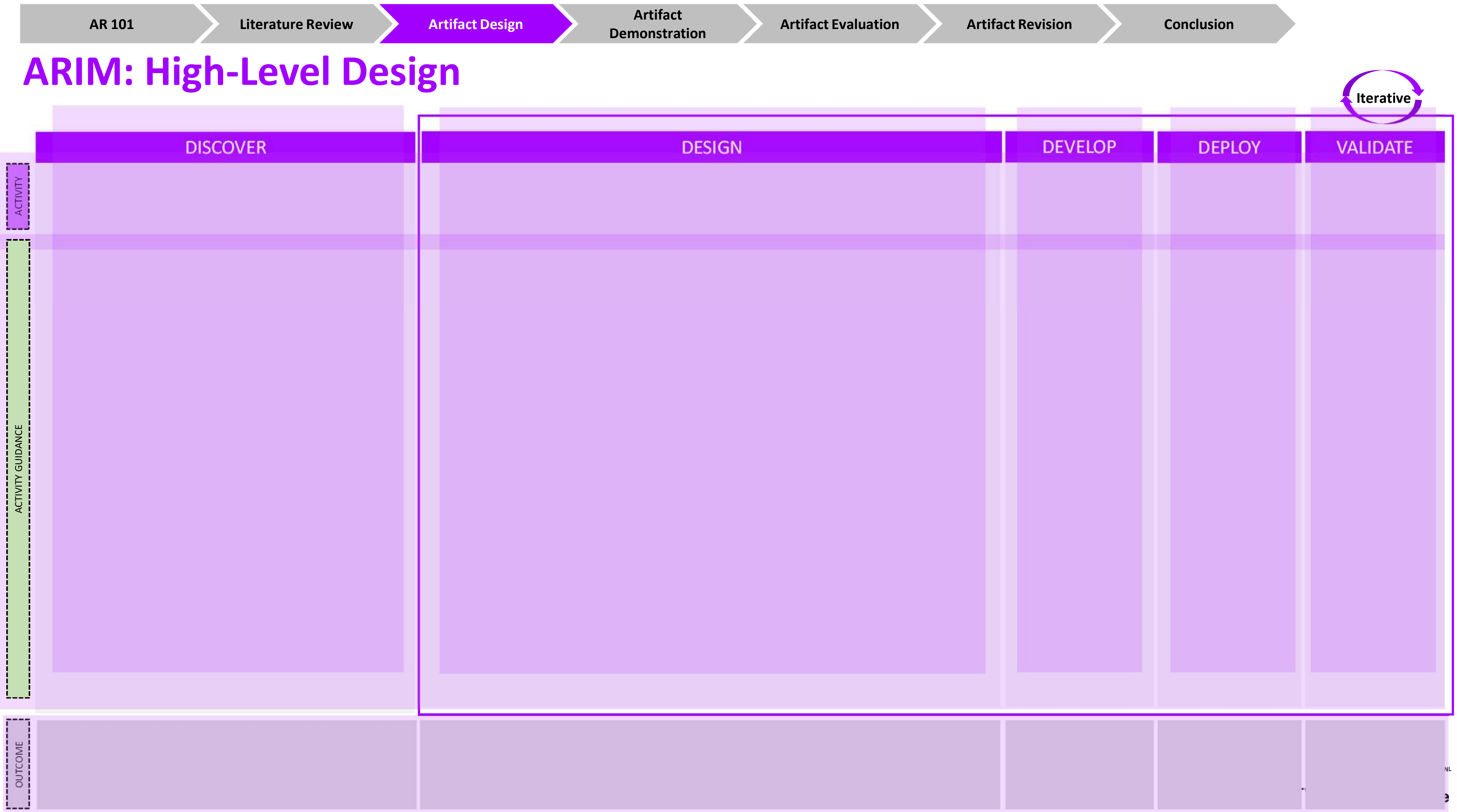
Success Factors for AR Adoption



E.g., head fatigue from prolonged usage of AR headset (as heavy as 1kg)

Photo credit: https://globalassistant.info/technology-acceptance-model-davis-1989-pdf-download-link-free/

ARIM: High-Level Design



AR 101 | Literature Review | **Artifact Design** | Artifact Demonstration | Artifact Evaluation | Artifact Revision | Conclusion

ARIM: High-Level Design

Iterative

	DISCOVER		DESIGN			DEVELOP	DEPLOY	VALIDATE
ACTIVITY	**Identify opportunity**	Assess process suitability for AR	Assess AR platform suitability: WebAR vs. Native AR vs. AR-on-headset	Assess AR dev. tool suitability	**Refine process requirements**	**Develop AR app**	**Deploy AR app**	**Test AR app with users**
ACTIVITY GUIDANCE	**Sub-activities:** **1. Define user personas + map user journey to identify desired outcomes and value drivers** **2. Define KPIs (CR3)** > How to measure the value drivers? **3. Collect process requirements (CR1)** > Ergonomics, data and privacy, health and safety regulations, etc. **4. Conduct a risk assessment** > (Non)-psychological risk factors e.g., user's fear of job loss, inadequate training				**Sub-activities:** **1. Refine process requirements collected from Discovery phase** > Functional requirements are captured as user stories > Non-functional requirements are used as part of acceptance criteria for relevant user stories	**Requirements:** **1. Flexible architecture for maintainability, agility, and time-to-market** > Microservice architecture > Agile development	**Requirements:** **1. CI/CD** **2. Design for cost optimization** E.g., Serverless architecture, auto-scaling **3. Design for performance** E.g., Multi-zone availability, auto-scaling **4. Design for security** E.g., Least-privilege, zero-trust zone, infra-as-code	**Sub-activities:** **1. Collect user feedback** **2. Validate value drivers + measure KPIs** **3. Create training materials**
OUTCOME	1. Stakeholder needs + expectations 2. User personas + user journeys	3. Prioritized use cases + value drivers + KPIs 4. Use case requirements 5. Risk assessment	1. AR platform(s) selection 2. AR development tools selection 3. Detailed functional/ non-functional requirements	4. High-level roadmap of prioritized AR use cases		1. Product backlog 2. Test cases 3. Working MVP	1. CI/CD pipelines 2. Cloud infrastructure configurations	1. Sprint review 2. Training materials 3. Validated value drivers/ KPIs

What Makes a Process a Good Candidate For AR?

Analyzes 39 AR use cases from academic + industry literature across multiple industries and synthesizes 6 common characteristics.

1. Content enriching
2. Work instructions
3. Hands-free access to content
4. Hard-to-simulate environment
5. Navigation
6. Collaboration

What Makes a Process a Good Candidate For AR?

Analyzes 39 AR use cases from academic + industry literature across multiple industries and synthesizes 6 common characteristics.

1. Content enriching
2. Work instructions
3. Hands-free access to content
4. Hard-to-simulate environment
5. Navigation
6. Collaboration

Photo credit: https://www.youtube.com/watch?v=4Vjajj7ZggA

What Makes a Process a Good Candidate For AR?

Analyzes 39 AR use cases from academic + industry literature across multiple industries and synthesizes 6 common characteristics.

1. Content enriching
2. Work instructions
3. Hands-free access to content
4. Hard-to-simulate environment
5. Navigation
6. Collaboration

Photo credit: https://www.terrauniversal.com/smart-gas-purged-glove-boxes.html

What Makes a Process a Good Candidate For AR?

Analyzes 39 AR use cases from academic + industry literature across multiple industries and synthesizes 6 common characteristics.

1. Content enriching
2. Work instructions
3. Hands-free access to content
4. **Hard-to-simulate environment**
5. Navigation
6. Collaboration

What Makes a Process a Good Candidate For AR?

Analyzes 39 AR use cases from academic + industry literature across multiple industries and synthesizes 6 common characteristics.

1. Content enriching
2. Work instructions
3. Hands-free access to content
4. Hard-to-simulate environment
5. Navigation
6. Collaboration

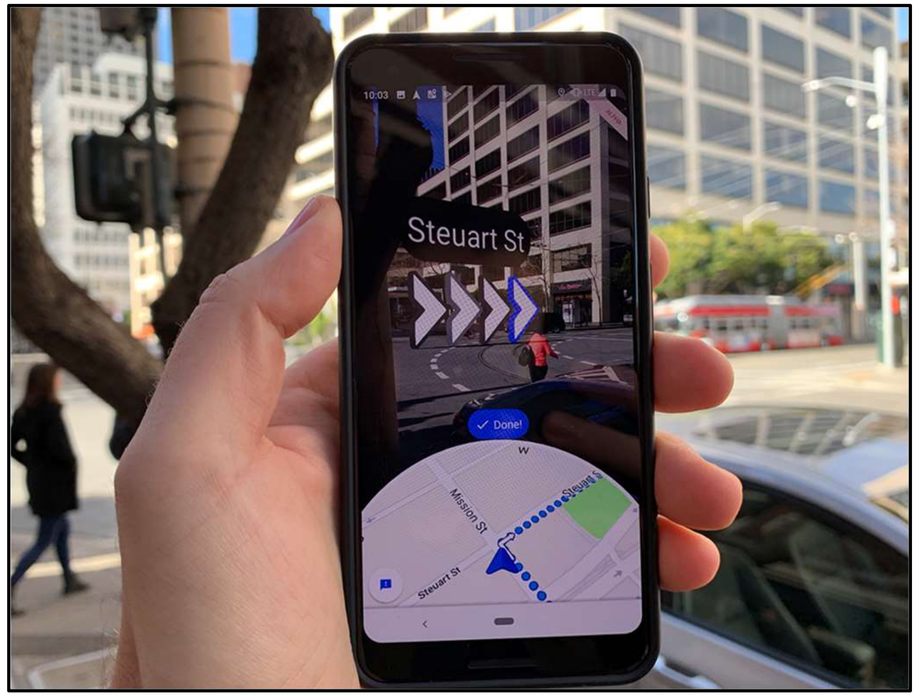


Photo credit: https://techcrunch.com/2020/10/01/google-maps-gets-improved-live-view-ar-directions

What Makes a Process a Good Candidate For AR?

Analyzes 39 AR use cases from academic + industry literature across multiple industries and synthesizes 6 common characteristics.

1. Content enriching
2. Work instructions
3. Hands-free access to content
4. Hard-to-simulate environment
5. Navigation
6. Collaboration

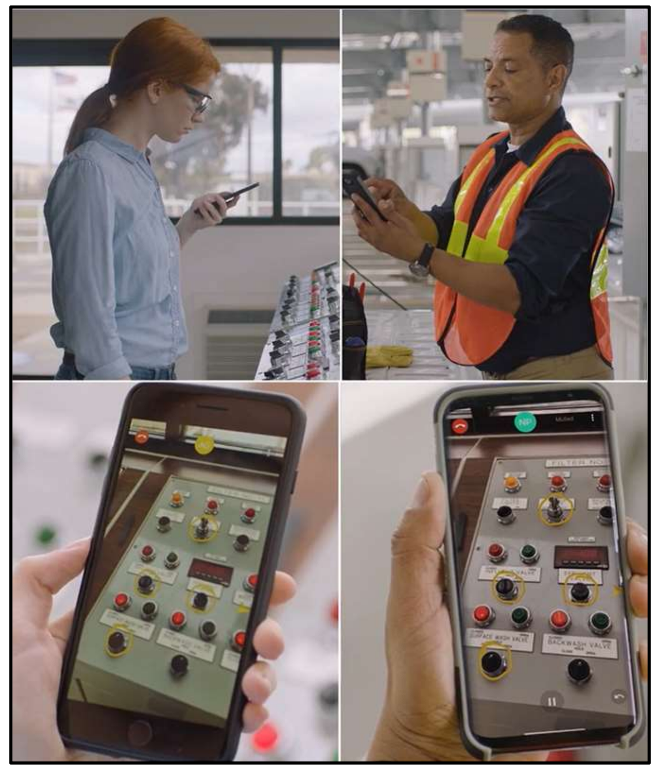


Photo credit: https://www.ptc.com/en/products/vuforia/vuforia-chalk

How to Choose Between AR Platforms + AR Dev. Tools?

In order to keep the methodology tool-agnostic, need to formulate a set of selection criteria for AR platforms + tools.

- ✗ Technical specs of AR platforms/ tools → Selection criteria (SC)
- ☑ AR adoption success factors → SC

AR Success Factor	*mapped to* →	High-level SC	*contextualized into* →	Low-level SC
SF1: AR solution should accommodate working conditions		Usage conditions-specific		Network connectivity: offline mode support
SF2: Ergonomics		Hardware-specific		Device weight

How to Choose Between AR Platforms?

23 selection criteria categorized into 1) Usage conditions-specific 2) Hardware-specific

1. Usage conditions-specific:

1. Lighting conditions
2. Network connectivity: offline mode support
3. Noise

4-5. Temperature + humidity

6-7. Drop-safe + water/dust-proof

8. Compliance with health/ safety standards
9. Hand usage: hands-free yes/ no
10. User interactions: hand, eye, headset tracking; voice commands
11. Movement restrictions

2. Hardware-specific:

1. Battery life
2. Device weight
3. Field-of-view

4-5. Camera + display resolution

6. Refresh rate

7-9. Storage + computation + remote rendering

10. Cross-device development
11. App download required
12. Cost: hardware + subscription

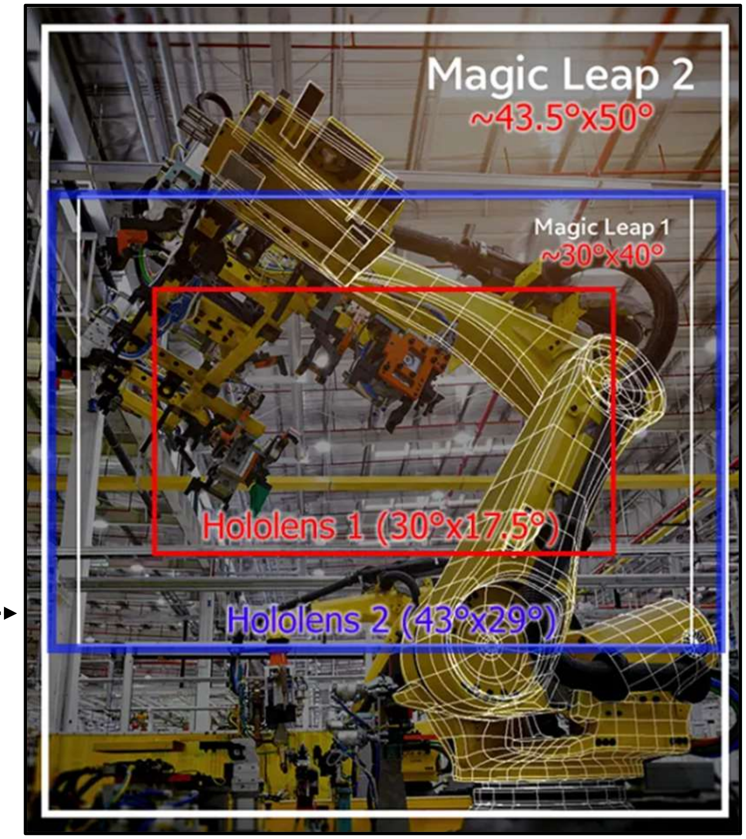


Photo credit: https://kguttag.com/2021/10/13/magic-leap-2-for-enterprise-really-plus-another-500m/

How to Choose Between AR Dev. Tools (Tracking + Rendering Engine)?

18 selection criteria categorized into 1) Tracking capabilities 2) Rendering capabilities 3) Ease of development 4) Licensing costs

1. Tracking capabilities
1-2. Fiducial + image tracking
3. Object tracking
4. Face tracking
5. Location tracking
6. Surface tracking
7. Spatial tracking
8. Other tracking techniques
9. Multi-marker tracking
10. Multi-user AR session
11. Depth tracking
12. Light effects

2. Rendering capabilities
1. Light estimation
2. Occlusion

3. Ease of development
1. Integration with other AR dev. tools
2. Simulation testing
3. No-code/ low-code development

4. Licensing cost
1. Open-source: yes/ no

Photo credit: https://www.youtube.com/watch?v=4Vjajj7ZggA

AR 101 > Literature Review > **Artifact Design** > Artifact Demonstration > Artifact Evaluation > Artifact Revision > Conclusion

ARIM: Final Design

Iterative

DISCOVER

ACTIVITY: Identify opportunity

ACTIVITY GUIDANCE

Sub-activities:

1. Define user personas + map user journey to identify desired outcomes and value drivers

2. Define KPIs
> How to measure the value drivers?

3. Collect process requirements
> Ergonomics, data and privacy, health and safety regulations, etc.

4. Conduct a risk assessment
> (Non)-psychological risk factors e.g., user's fear of job loss, inadequate training

ACTIVITY: Assess process suitability for AR

ACTIVITY GUIDANCE

Characteristics which make a process ideal for AR:

1. Content enriching
E.g., AR monitoring dashboard anchored to a physical machine, AR artbook

2. Work instructions
E.g., AR-guided work instructions

3. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy

4. Hands-free access to contents
E.g., surgeons viewing patient data during surgery

5. Navigation
E.g., AR-guided emergency & rescue

6. Collaboration
E.g., remote assist

OUTCOME

1. Stakeholder needs + expectations
2. User personas + user journeys
3. Prioritized use cases + value drivers + KPIs
4. Use case requirements
5. Risk assessment

DESIGN

ACTIVITY: Assess AR platform suitability: WebAR vs. Native AR vs. AR-on-headset

ACTIVITY GUIDANCE

Selection criteria:

1. Usage conditions-specific:
1. Lighting conditions
2. Network connectivity: offline mode support yes/ no
3. Noise
4-5. Temperature + humidity
6-7. Drop-safe + water/dust-proof
8. Compliance with health/ safety standards
9. Hand usage: hands-free yes/ no
10. User interactions: hand, eye, headset tracking; voice commands
11. Movement restrictions

2. Hardware-specific:
1-2. Battery life + device weight
3. Field-of-view
4-5. Camera + display resolution
6. Refresh rate
7-9. Storage + computation + remote rendering
10. Cross-device development
11. App download required
12. Cost: hardware + subscription

ACTIVITY: Assess AR dev. tool suitability

ACTIVITY GUIDANCE

Selection criteria:

1. Tracking capability
1-2. Fiducial+image tracking
3. Object tracking
4. Face tracking
5. Location tracking
6. Surface tracking
7. Spatial tracking
8. Other tracking techniques
9. Multi-marker tracking
10. Multi-user AR session
11. Depth tracking
12. Light effects

2. Rendering capability
1. Light estimation
2. Occlusion

3. Ease of development
1. Integration with other AR dev. tools
2. Simulation testing
3. No-code/ low-code dev.

4. Licensing cost
1. Open-source: yes/ no

ACTIVITY: Refine process requirements

ACTIVITY GUIDANCE

Sub-activities:

1. Refine process requirements collected from Discovery phase
> Functional requirements are captured as user stories
> Non-functional requirements are used as part of acceptance criteria for relevant user stories

OUTCOME

1. AR platform(s) selection
2. AR development tools selection
3. Detailed functional/ non-functional requirements
4. High-level roadmap of prioritized AR use cases

DEVELOP

ACTIVITY: Develop AR app

ACTIVITY GUIDANCE

Requirements:

1. Flexible architecture for maintainability, agility, and time-to-market
> Microservice architecture
> Agile development

OUTCOME

1. Product backlog
2. Test cases
3. Working MVP

DEPLOY

ACTIVITY: Deploy AR app

ACTIVITY GUIDANCE

Requirements:

1. CI/CD

2. Design for cost optimization
E.g., Serverless architecture, auto-scaling

3. Design for performance
E.g., Multi-zone availability, auto-scaling

4. Design for security
E.g., Least-privilege, zero-trust zone, infra-as-code

OUTCOME

1. CI/CD pipelines
2. Cloud infrastructure configurations

VALIDATE

ACTIVITY: Test AR app with users

ACTIVITY GUIDANCE

Sub-activities:

1. Collect user feedback

2. Validate value drivers + measure KPIs

3. Create training materials

OUTCOME

1. Sprint review
2. Training materials
3. Validated value drivers/ KPIs

WebAR Prototype: Use Case Introduction

Before

Now: Dead

WebAR Prototype: Discover Phase

Mapping user personas and user journeys to uncover problem/ opportunity

Stage	Before watering		During watering	After watering
Plant Owner	**Happy** “What a great day. Think I might water the plant”	**Concerned** “Wait. When’s the last time I watered it?	**Unsure** “Vaguely remember watering it last week. Might as well water it again”	**Worried** “The leaves look brown. Only if I know what is going on. Maybe I should note down how often I water it.” [Never did]
House Sitter	**Happy** “What a great day. Think I might water the plant”		**Indifferent** “No idea when the plant was last watered. But I’m only house-sitting for 2 days. Might as well water them.”	**Indifferent** “The leaves look brown, but it are not even my plant. Perhaps I leave a note.” [Never did]

WebAR Prototype: Discover Phase

Mapping user personas and user journeys to uncover problem/ opportunity

Stage: Before watering → During watering → After watering

Plant Owner House Sitter

Happy
"What a great day. Think I might water the plant"

Curious and informed
"When was the plan last watered? Does it need water now? Let's check out the watering history and the current soil moisture level on the AR dashboard!"

Happy
"Ahh the soil moisture is below the ideal level, and I haven't watered in a few days. Time to water now."

Worried but no worries
"The leaves look brown. But at least I can check out some videos about how to care for the plant + note the health status of the plant on the AR dashboard. That way I can keep monitoring it."

WebAR Prototype: Design Phase

Choose 1) AR Platform 2) Tracking engine 3) Rendering engine

AR PLATFORM

WebAR

No app download/ install required

TRACKING ENGINE

Image tracking; open-source

RENDERING ENGINE

three.js

Open-source; wide community support

WebAR Prototype: Design Phase

Choose 1) AR Platform 2) Tracking engine 3) Rendering engine

AR PLATFORM

WebAR

No app download/ install required

TRACKING ENGINE

Image tracking; open-source

RENDERING ENGINE

three.js

Open-source; wide community support

WebAR Prototype: Design Phase

Choose 1) AR Platform 2) Tracking engine 3) Rendering engine

AR PLATFORM

WebAR

No app download/ install required

TRACKING ENGINE

Image tracking; open-source

RENDERING ENGINE

three.js

Open-source; wide community support

WebAR Prototype: Design Phase

Choose 1) AR Platform 2) Tracking engine 3) Rendering engine

AR PLATFORM

WebAR

No app download/ install required

TRACKING ENGINE

Image tracking; open-source

RENDERING ENGINE

three.js

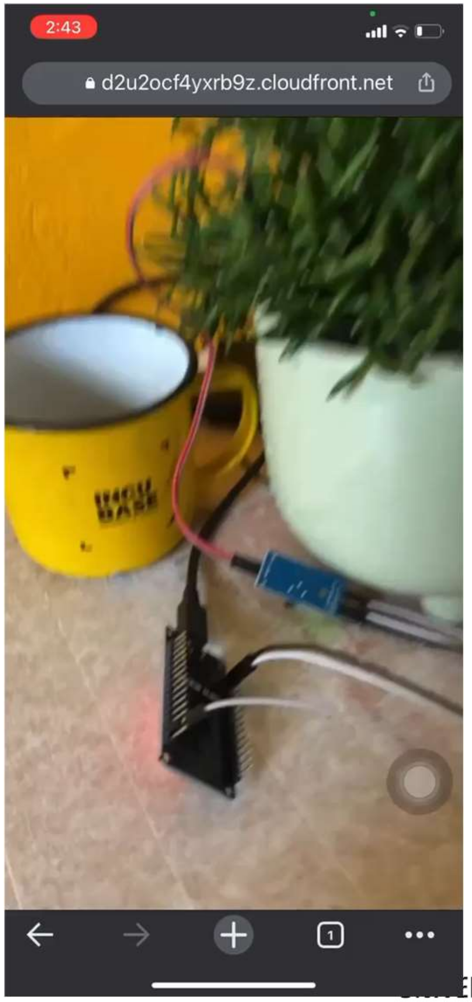
Open-source; wide community support

WebAR Prototype: Develop + Deploy + Validate Phase

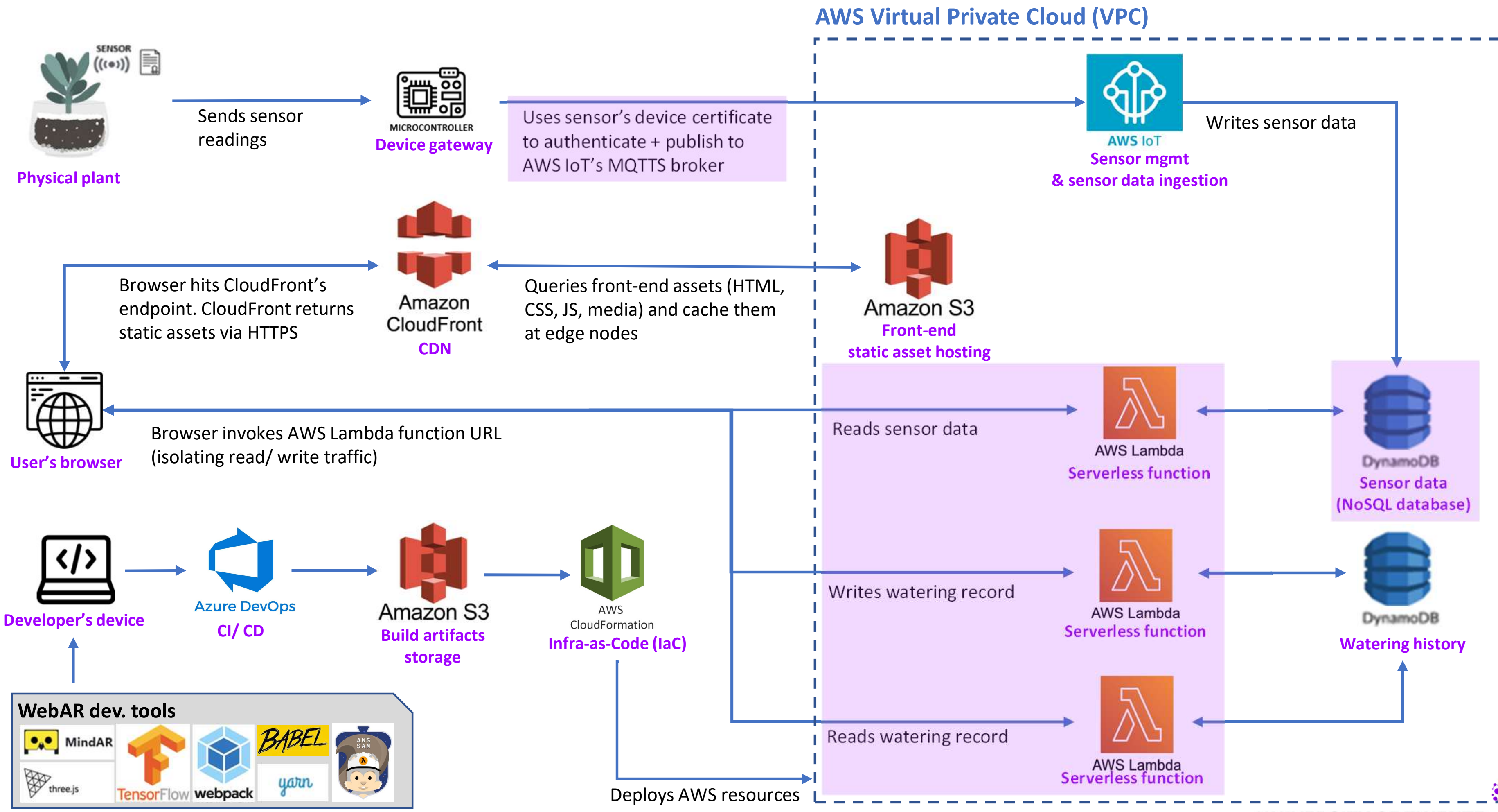
Image marker

Soil moisture sensor

Microcontroller connected to sensor



WebAR Prototype: Develop + Deploy + Validate Phase



AR 101 | Literature Review | Artifact Design | Artifact Demonstration | **Artifact Evaluation** | Artifact Revision | Conclusion

Interviews with 3 Accenture Domain Experts (4,3)

Iterative

	DISCOVER		DESIGN			DEVELOP	DEPLOY	VALIDATE
ACTIVITY	Identify opportunity (2,7)	Assess process suitability for AR (3,7)	Assess AR platform suitability: WebAR vs. Native AR vs. AR-on-headset (5)	Assess AR dev. tool suitability (4)	Refine process requirements (2,7)	Develop AR app (2,7)	Deploy AR app (2,7)	Test AR app with users (2,7)
ACTIVITY GUIDANCE	**Sub-activities:** **1. Define user personas + map user journey to identify desired outcomes and value drivers** **2. Define KPIs (CR3)** > How to measure the value drivers? **3. Collect process requirements (CR1)** > Ergonomics, data and privacy, health and safety regulations, etc. **4. Conduct a risk assessment** > (Non)-psychological risk factors e.g., user's fear of job loss, inadequate training	**Characteristics which make a process ideal for AR:** 1. Content enriching E.g., AR monitoring dashboard anchored to a physical machine, AR artbook **2. Work instructions** E.g., AR-guided work instructions **3. Hard-to-simulate environment** E.g., 3D mesh of crime scene, 3D patient anatomy **4. Hands-free access to contents** E.g., surgeons viewing patient data during surgery **5. Navigation** E.g., AR-guided emergency & rescue 6. Collaboration E.g., remote assist	**Selection criteria:** **1. Usage conditions-specific:** 1. Lighting conditions 2. Network connectivity: offline mode support yes/ no 3. Noise 4-5. Temperature + humidity 6-7. Drop-safe + water/dust-proof 8. Compliance with health/ safety standards 9. Hand usage: hands-free yes/ no 10. User interactions: hand, eye, headset tracking; voice commands 11. Movement restrictions **2. Hardware-specific:** 1-2. Battery life + device weight 3. Field-of-view 4-5. Camera + display resolution 6. Refresh rate 7-9. Storage + computation + remote rendering 10. Cross-device development 11. App download required 12. Cost: hardware + subscription	**Selection criteria:** **1. Tracking capability** 1-2. Fiducial+image tracking 3. Object tracking 4. Face tracking 5. Location tracking 6. Surface tracking 7. Spatial tracking 8. Other tracking techniques 9. Multi-marker tracking 10. Multi-user AR session 11. Depth tracking 12. Light effects **2. Rendering capability** 1. Light estimation 2. Occlusion **3. Ease of development** 1. Integration with other AR dev. tools 2. Simulation testing 3. No-code/ low-code dev. **4. Licensing cost** 1. Open-source: yes/ no	**Sub-activities:** **1. Refine process requirements collected from Discovery phase** > Functional requirements are captured as user stories > Non-functional requirements are used as part of acceptance criteria for relevant user stories	**Requirements:** **1. Flexible architecture for maintainability, agility, and time-to-market (CR8)** > Microservice architecture > Agile development	**Requirements:** **1. CI/CD (CR9)** **2. Design for cost optimization (CR10)** E.g., Serverless architecture, auto-scaling **3. Design for performance (CR12)** E.g., Multi-zone availability, auto-scaling **4. Design for security (CR13)** E.g., Least-privilege, zero-trust zone, infra-as-code	**Sub-activities:** **1. Collect user feedback (CR15)** **2. Validate value drivers + measure KPIs (CR4)** **3. Create training materials (CR11)**
OUTCOME	1. Stakeholder needs + expectations 2. User personas + user journeys	3. Prioritized use cases + value drivers + KPIs 4. Use case requirements 5. Risk assessment	1. AR platform(s) selection 2. AR development tools selection 3. Detailed functional/ non-functional requirements	4. High-level roadmap of prioritized AR use cases		1. Product backlog 2. Test cases 3. Working MVP	1. CI/CD pipelines 2. Cloud infrastructure configurations	1. Sprint review 2. Training materials 3. Validated value drivers/ KPIs

Revised AR Implementation Methodology

DISCOVERY*

Produces ARIF's inputs:

- User personas
- User journeys
- List of potential AR use cases to be validated using ARIF
- Preliminary process requirements (i.e., use case requirements): incl. ergonomics, health and safety standards, privacy and data protection
- Risk assessment: (non)-psychological risks

** Accenture's existing frameworks*

AR IMPLEMENTATION METHODOLOGY: GUIDING AR USE CASE ASSESSMENT

ACTIVITY

ACTIVITY GUIDANCE

Assess process suitability for AR

Characteristics which make a process ideal for AR:

1. Location-based context
E.g., AR dashboard for machine status monitoring, AR-guided work instructions anchored to a machine

2. Hard-to-simulate environment
E.g., 3D mesh of crime scene, 3D patient anatomy for pre-surgical planning, virtual product prototyping

3. Hands-free access to content
E.g., surgeons viewing patient data during surgery, nuclear power plant workers can access contents hands-free while operating a glovebox

4. Remote assist
E.g., Remote workers visually guide and collaborate with local workers without geographical constraints.

5. Navigation
E.g., AR-guided emergency & rescue

Assess AR platform suitability**:
WebAR vs. Native AR vs. AR-on-headset

Selection criteria:

1. Usage conditions-specific:
1. Lighting conditions
2. Network connectivity: offline mode support yes/ no
3. Noise
4-5. Temperature + humidity
6-7. Drop-safe + water/dust-proof
8. Health/ safety compliance
9. Hand usage
10. User interactions: hand, eye, headset tracking; voice commands
11. Movement restrictions: e.g., tethered AR headsets cause more restrictions than a phone/ tablet/ non-tethered AR headsets

2. Hardware-specific:
1-2. Battery life + device weight
3. Field-of-view
4-5. Camera + display resolution
6. Refresh rate
7-9. Storage + computation + remote rendering
10. Cross-device development
11. App download required
12. Heat distribution
13. Cost: hardware + subscription

Assess AR dev. tool suitability**: Tracking + Rendering Engine

Tracking and rendering engines are benchmarked using the following criteria.

1. Tracking capabilities: Different use cases require different tracking capabilities
1-2. Fiducial + image tracking
3. Object tracking
4. Face tracking
5. Location tracking
6. Surface tracking
7. Spatial tracking
8. Other tracking techniques
9. Multi-marker tracking
10. Multi-user AR session
11. Depth tracking
12. Light effects

2. Rendering capabilities: Rendering speed is affected by network connection + rendering engine's design + hardware capabilities, and therefore not assessed here.
1. Light estimation: more realistic rendering
2. Occlusion: more realistic rendering

3. Ease of development:
1. Integration with other AR dev. tools: checks which tracking engine integrates with which rendering engine
2. Simulation/ remote testing:
3. No-code/ low-code development

4. Licensing cost
1. Open-source: yes/ no

Refine process requirements

Activities:
1. Refine process requirements collected from Discovery phase
> Functional requirements are captured as user stories
> Non-functional requirements are used as part of acceptance criteria for relevant user stories

AGILE*:
DESIGN > DEVELOP > DEPLOY > VALIDATE

Receives ARIF's outputs:

- Validation if AR is suitable for target use cases
- If yes, AR platform selection, AR development tools selection, refined process requirements, and a high-level roadmap of prioritized AR use cases

*** Supplemented with Definition Tables + Decision Matrices*

Academic and Practical Contributions

Academic contributions:

1. Process suitability for AR assessment: **5 process characteristics**
2. AR platform suitability assessment: **24 selection criteria**
3. AR development tool suitability assessment: **18 selection criteria**

Practical contributions:

1. Industry-agnostic, tool-agnostic AR Implementation Methodology (tailored for Accenture)
2. AR Platform Decision Matrix (Appendix)
3. AR Development Tool Decision Matrix (Appendix)
4. Reference cloud architecture for WebAR application

Limitations, Recommendations & Future Works

Limitations + Recommendations:

1. Proposed process characteristics serve as "positive indicators": **define "negative indicators"**
2. Non-exhaustive AR Platform/ AR Development Tool Decision Matrices: **active maintenance**
3. AR technology evolves, there might be new success factors which are not yet incorporated in the ARIM: **active maintenance**
4. Only 3 Accenture experts were interviewed: **more (non)-Accenture interviews**

Future Works:

1. Addressing known limitations
2. Expand to Virtual Reality (VR)
3. Expand to Assisted Reality

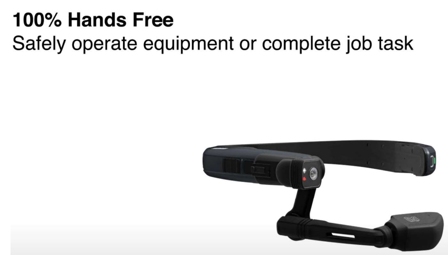


Photo credit: https://youtu.be/7yjQ5LYT9ok

Current State and Future State of AR Technology

Based on author's observations; not backed by empirical evidence

1. Addressing existing hardware limitations:
- CPU/ GPU + heat distribution
- Remote rendering + 5G
- Cost

2. Addressing existing software limitations:
- More accurate tracking
- More realistic rendering

3. Augmenting for complex human senses:
- Today's AR: primarily vision + hearing
- Tomorrow's AR: touch, taste, smell

Photo credit: https://neuronewsinternational.com/surgical-theater-ar-vr-neurosurgery-technologies-israel/

Thank You

Appendix: Definition Table of Characteristics of Ideal Process for AR

#	Process Characteristic	Definition
1	Location-based context	A process is ideal for AR when worker productivity is improved when provided location-based context i.e., (real-time) information as anchored to a physical object or environment. For example, a shopfloor manager can view an AR dashboard with real-time sensor data as anchored to a physical equipment to quickly inspect the current status of the equipment. Another example is an AR-guided work instructions anchored to a physical machine which allows workers to approach the machine and access the work instructions on demand as the worker carry out a complex task (video).
2	Hard-to-simulate environment	A process is ideal for AR when worker productivity is improved when allowed to interact with AR contents which are hard to be simulated otherwise in real life. For example, instead of relying on 2D medical scan images, surgeons can view a 3D model of a patient anatomy for pre-surgical planning. In this case, patient anatomy is considered a hard-to-simulate environment. Additional examples are AR-enabled product prototyping (experimenting with different design before actual product fabrication), 3D mesh of a crime scene (video), construction planning (video), layout planning (video), and bridge inspection (video).
3	Hands-free access to content	A process is ideal for AR when worker productivity is improved when provided access to content without having to use their hands. For example, surgeons can view patient's medical records during surgeries using voice commands (video).
4	Remote assist	A process is ideal for AR when worker productivity is improved when remote workers can guide and collaborate without geographical constraints. For example, through live camera streaming, a remote worker can share the same view as the local worker and makes live, virtual annotations on the view to guide the local worker through a task (video).
5	Navigation	A process is ideal when worker productivity is improved when guided to a target destination by virtual AR contents. For example, a traveler can be guided to their gate at an unfamiliar airport by following virtual arrows for directions (photo).

Appendix: Definition Table of AR Platform Selection Criteria 1/2

#	Category	Selection Criteria	Definition
1	Usage conditions-specific	Lighting conditions	Harsh lighting conditions (too dim or too bright) will require AR platforms whose tracking engine must be robust enough to process live camera feed of degrading quality and detect a marker.
2		Network connectivity	When deployed in environments without stable internet connection like shopfloors, ideal AR platforms are the ones with offline mode support.
3		Noise	When deployed in loud environments like shopfloors, ideal AR platforms are those with noise-cancelling microphones.
4-7		Temperature + Humidity + Drop-safe + Water/dust-proof	When deployed in rugged conditions, ideal AR platforms are those built for extreme temperature, humidity, drop-safe, waterproof, and dustproof.
8		Health/ safety compliance	Some use cases will require AR platforms to comply with specific health and safety standards e.g., hardhat integration, medical certifications for clean room usage, eye safety.
9		Hand usage	Some tasks require users to use both of their hands e.g., surgeons carrying out a surgery (making AR headsets most ideal) while some tasks occupy only one hand, allowing users to use their other hand to hold a mobile device (making it possible to use webAR or native AR).
10		10. User interactions	Different AR platforms support different built-in user interactions e.g., voice/ gesture/ gaze controls for an intuitive and enhanced user experience.
11		11. Movement restrictions	Some tasks require users to have a full range of movement (e.g., shopfloor operators), making non-tethered AR headsets, webAR, and native AR ideal options. Some other tasks require only a limited range of movements, making tethered AR headsets an acceptable option in exchange for better tracking and rendering performance and lower latency since the tethered headset usually is connected to a powerful computer.

Appendix: Definition Table of AR Platform Selection Criteria 2/2

#	Category	Selection Criteria	Definition
1	Hardware-specific	Battery life	The longer the battery life, the fewer charges are required between usage.
2		Device weight	The heavier the device, the more fatigue it causes, especially head fatigue when using AR headsets.
3		Field-of-view (FoV)	The wider the FoV, the bigger virtual contents users can view and the more immersive the AR experience feels. For virtual product prototyping, a big FOV is preferable while for other use cases such as an AR monitoring dashboard for factory equipment, an average sized FoV might be acceptable.
4		Camera resolution	The higher the camera resolution, the higher quality video the camera can capture. It is valuable, for example, when the live camera is streamed to a remote worker for the use case of AR-guided remote assistance.
5		Display resolution	The higher the display resolution, the higher fidelity the virtual contents are.
6		Refresh rate	The higher refresh rate, the smoother the virtual contents appear.
7-9		Storage + computation + remote rendering	Storage, computation, and remote rendering dictate how much tracking and rendering can be performed locally on the AR device (no latency) or remotely in the cloud (requiring less powerful AR devices but results in higher latency).
10		Cross-device development	Allows developers to develop a WebAR, native AR, and AR-on-headset application once and deploy the application on multiple browsers, Android/ iOS devices, and AR headsets, respectively.
11		App download required	Refers to if a user needs to download and install the AR app to their device. WebAR is the only platform that does not require users to download and install WebAR apps since WebAR runs directly from a browser, giving it an advantage over native AR and AR headsets.
12		Heat distribution	Refers to how much heat an AR device produces while running and how fast the heat can dissipate because of the thermal model of the AR device. This factor is important because heating AR devices, especially AR headsets, can cause skin burns and affect user experience.
13		Cost: hardware + subscription	Refers to the cost of using the AR platforms (hardware cost + subscription cost).

Appendix: Definition Table of AR Dev. Tool Selection Criteria 1/2

#	Category	Selection Criteria	Definition
1-7	Tracking capabilities	Fiducial tracking; Image tracking; Face tracking; Location tracking; Object tracking; Surface tracking; Spatial tracking	Different use cases require different tracking techniques. In the example of an art book in here, the art book is implemented using an image tracking engine which allows users to scan an image of a sculpture in the artbook and view a 3D model of the sculpture rendered on top of the image. On the other hand, spatial tracking is more appropriate for implementing, say, an AR-guided evacuation route for an underground mine since it would not be feasible to attach image markers to rock faces and make sure the image markers stay put.
8		Depth tracking	Depth tracking is an additional capability of tracking engines to understand the physical environment. With depth knowledge, tracking engines can instruct rendering engines to occlude virtual objects if they are behind physical objects for a more realistic experience.
9		Other tracking	As more computer vision technology evolves, more tracking techniques are being developed. This criterion serves as a catch-all for those techniques.
10		Multi-marker tracking	Refers to a capability of tracking engines to detect and track multiple markers in a single video frame, creating a richer experience (picture).
11		Multi-user tracking	Refers to the ability of tracking engines to synchronize across multiple devices and allow multiple users to join a single AR session. For example, an AR-guided remote assistance solution requires the use of multi-user tracking (video).
12		Lighting effects	Refers to additional capabilities of tracking engines such as light estimate i.e., predicting the lighting conditions of the physical environment (picture).

Appendix: Definition Table of AR Dev. Tool Selection Criteria 2/2

#	Category	Selection Criteria	Definition
1	Rendering capabilities	Light estimates	Using the light estimate data from tracking engines, rendering engines can shade the virtual contents to match the lighting conditions of the physical environment for more realistic virtual contents (picture).
2		Occlusion	Using the depth data from tracking engines, rendering engines can occlude virtual objects which stand behind physical objects for more realistic virtual contents (picture).
1	Ease of develop-ment	Integration with other AR development tools	Cross-references which tracking engines integrate with which rendering engines. Refresher: an AR application requires both tracking and rendering engines, and the two engines need to integrate with each other.
2		Simulation/ remote testing	Allows developers to test and debug AR applications more quickly.
3		Low-code/ no-code development	Allows business users with little to no programming knowledge to create new AR experiences e.g., allowing shopfloor operators to create new AR-guided work instructions.
1	Licensing cost	Open-source	Checks if the tracking/ rendering engines are open-source or not.

Appendix: AR Platform Suitability Decision Matrix 1/4

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by: 1) Usage condition-specific 2) Hardware

	Selection Criteria	WebAR (web browser)	Native AR (Android, iOS)	Varjo XR-3 (2020)	HoloLens 2 (2019)	Magic Leap 2 (2022)	Meta Quest Pro (2022)	Vuzix Blade 2 (2022)	Vuzix M400 (2020)	Google Glass 2 (2019)
1. Usage conditions-specific selection criteria	1. Lighting conditions	Irrespective of AR platforms, their tracking engine performs better or worse in different light conditions due to the fluctuating quality of video frames being captured in different light conditions, making it easy or hard for the tracking engine's computer vision algorithms to detect a marker in those video frames. In order to choose an AR platform that best accommodates the target lighting conditions: 1) Test different candidate AR platforms in different lighting conditions and choose the most performant one 2) Or: customize the tracking engine's computer vision algorithms 3) Or: customize the camera's properties to improve the quality of the captured video frames e.g., reduce the camera's exposure level in an overly bright environment (source)								
	2. Network connectivity	Offline mode supported when implementing Service Worker	Offline mode supported	Offline mode supported with offline subscription	Work instructions in Dynamics 365 Guides support offline mode with limitations (e.g., no video calls)	No info about offline mode support	No info about offline mode support	Offline mode supported	Offline mode supported	No info about offline mode support
	3. Noise	Device-specific	Device-specific	No info	5 noise cancelling microphones	No info	No info	2 noise-cancelling microphones	3 noise-cancelling microphones	3 noise cancelling microphones
	4. Operating temperature	Device-specific	Device-specific	No info	10°C to 35°C	10°C to 30°C	No info	0°C to 35°C	-20°C to 45°C	0°C to 35°C
	5. Operating humidity	Device-specific	Device-specific	No info	No info	No info	No info	0% to 95%	0% to 95%	5% to 95%
	6. Drop-safe	Device-specific	Device-specific	No info	No info	No info	No info	No info	MIL-STD-810G certification	No info
	7. Water/ Dustproof	Device-specific	Device-specific	No info	IP50 Dust proof	No info	No info	No info	IP67 Dust + water protection certification	IP53 (Resistant to water spray and limited dust ingression)

Appendix: AR Platform Suitability Decision Matrix 2/4

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by: 1) Usage condition-specific 2) Hardware

	Selection Criteria	WebAR (web browser)	Native AR (Android, iOS)	Varjo XR-3 (2020)	HoloLens 2 (2019)	Magic Leap 2 (2022)	Meta Quest Pro (2022)	Vuzix Blade 2 (2022)	Vuzix M400 (2020)	Google Glass 2 (2019)
1. Usage conditions-specific selection criteria	8. Compliance with health/ safety standards	Device-specific	Device-specific	No info	• ANSI Z87.1, CSA Z94.3 and EN 166 certifications for eye safety. • Hardhat-integrated; • Compliant with regulated environments e.g., clean rooms;	IEC 60601 certifications for medical use	No info	• UV protection lens; • ANSI Z87.1 for eye safety.;	• IEC 60601 certifications for medical use • Comes with hardhat mount;	No info
	9. Hand usage	One hand occupied to hold mobile device.		Hands-free	Hands-free	Hands-free with one hand-held controller	Hands-free with two hand-held controllers	Hands-free	Hands-free	Hands-free
	10. User interactions	Hand tracking possible when implementing hand tracking engines like Ultraleap and Handtrack.js; Voice commands are possible using speech recognition APIs like Web Speech API (for web AR) or Cordova Speech Recognition API (native AR Android/ iOS);		Eye tracking; Headset and controller tracking;	Voice command; Eye tracking; Headset tracking; Hand tracking;	Eye tracking; Hand tracking; Voice commands; Controller tracking	Eye tracking; Controller tracking; Hand tracking;	Touchpad gestures; Voice control;	Voice control;	Touchpad gestures; voice commands;
	11. Movement restrictions	Non-tethered		Tethered	Non-tethered	Non-tethered but comes with a wired, pocket-size external processor called Compute Pack	Non-tethered	Non-tethered	Non-tethered	Non-tethered

Appendix: AR Platform Suitability Decision Matrix 3/4

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by: 1) Usage condition-specific 2) Hardware

	Selection Criteria	WebAR (web browser)	Native AR (Android, iOS)	Varjo XR-3 (2020)	HoloLens 2 (2019)	Magic Leap 2 (2022)	Meta Quest Pro (2022)	Vuzix Blade 2 (2022)	Vuzix M400 (2020)	Google Glass 2 (2019)
2. Hardware-specific selection criteria	1. Battery life	Device-specific	Device-specific	No info	2-3 hours	3.5 hours	1-2 hours	No info	2 hours with external battery possible	8 hours
	2. Device weight	Device-specific	Device-specific	594 g + headband 386 g	566 g	260 g	722 g	No info	182 g	51 g
	3. Field of view (horizontal)	N/A		115°	43°	70°	106°	20°	16.8°	83°
	4. Camera resolution	Device-specific	Device-specific	12 MP	8 MP	12.6 MP	No info	8 MP	12.8 MP	8 MP
	5. Display resolution (per eye)	Device-specific	Device-specific	Focus area (27° x 27°) at 1920 x 1920 pixel; Peripheral area at 2880 x 2720 pixel;	1440 x 936 pixel	1440 x 1760 pixel	1800 x 1920 pixel	480 x 480 pixel	854 x 480 pixel	640 x 360 pixel
	6. Refresh rate	Depending on the tracking and rendering engine		90 Hz	60 Hz	120 Hz	90 Hz	No info	No info	No info
	7. Storage capacity	Device-specific	Device-specific	No info	4GB RAM; 64GB storage;	16GB RAM; 256GB storage;	12GB RAM; 256GB storage;	40GB storage	6GB RAM; 64GB storage	3GB RAM; 32GB storage
	8. Computation capacity	Device-specific	Device-specific	No info	CPU: Octa-core Kryo 385; GPU: Adreno 630	CPU: AMD 7nm Quad-core Zen2 X86 core; GPU: AMD GFX10.2	CPU: Octa-core Kryo 585; GPU: Adreno 650	CPU: Quad Core ARM	CPU: 8 Core 2.52Ghz Qualcomm XR1	CPU: Octa-core Kryo; GPU: Adreno 615
	9. Remote rendering	No native integration	No native integration	Yes – Varjo Reality Cloud	Yes – Azure Remote rendering	Yes – Integrates with NVIDIA CloudXR	No info	No info	No info	No info

Appendix: AR Platform Suitability Decision Matrix 4/4

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by: 1) Usage condition-specific 2) Hardware

	Selection Criteria	Selection criteria description	WebAR (web browser)	Native AR (Android, iOS)	Varjo XR-3 (2020)	HoloLens 2 (2019)	Magic Leap 2 (2022)	Meta Quest Pro (2022)	Vuzix Blade 2 (2022)	Vuzix M400 (2020)	Google Glass 2 (2019)
2. Hardware-specific selection criteria	10. Cross-device develop-ment	Allows developers to develop a webAR, native AR, and AR-on-headset application once and deploy the application on multiple browsers, Android/ iOS devices, and AR headsets, respectively.	Likely – Most webAR tracking and rendering engines are built upon browser's natively supported features such as WebGL – see example of browser requirements for 8th Wall tracking engine	Likely – Some tracking engines like Vuforia support build for both Android and iOS. ARCore only supports Android. ARKit only supports iOS – see AR Development Tool Decision Matrix for details	Yes – integrates with OpenXR*;	Yes – integrates with OpenXR;	Yes – integrates with OpenXR;	No info	No integration with OpenXR (yet)	No integration with OpenXR (yet)	No integration with OpenXR (yet)
	11. App download required	Refers to if a user needs to download and install the AR app to their device.	No	Yes							
	12. Heat distribution	Refers to how much heat an AR device produces while running and how fast the heat dissipates according to the thermal design of the AR device. Note heating AR devices, especially AR headsets, can cause skin burns and affect user experience.	It appears that there is no standard measure for benchmarking the thermal model of different AR devices. Heat distribution is primarily a hardware problem with the chips being one of the main heat-generating components (source). Therefore, it is recommended to experiment with different AR devices for the target usage conditions and select the most comfortable headset.								
	13. Cost	Refers to the cost of using the AR platforms.	Device-specific	Device-specific	€6.495 + mandatory XR Subscription	€ 3.849,00+ + optional HoloLens subscription	~€3,167+ ($3.299+)	€1.799,99	€1,669.80	€2.311,10	~€1,090 ($1,144)

Appendix: AR Dev. Tool Suitability Decision Matrix 1/3

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by:
1) Tracking capabilities 2) Rendering capabilities 3) Ease of development 4) Licensing cost

Tracking engine | **Rendering engine** | **Tracking + Rendering**

	Selection Criteria (SC)	MindAR	AR.js	WebXR	8th Wall	Lightship ARDK (2021)	Vuforia (2011)	Azure Spatial Anchors	ARCore (2018)	ARKit (2017)	Manifest (2017)	Three.js	A-frame	Unity	Unreal	RealityKit	Adobe Aero (2019)	Meta Spark Studio (2017)
	AR platforms supported	WebAR	WebAR	WebAR	WebAR	Native AR (Android, iOS)	Native AR, AR headset (HoloLens 2, Magic Leap 2, Vuzix, RealWear)	Native AR (Android, iOS), AR headset (HoloLens)	Native AR (Android)	Native AR (iOS)	Native AR, AR headset (HoloLens, Magic Leap, Realwear)	WebAR	WebAR	Native AR, AR headset	Native AR, AR headset	Native AR (iOS)	WebAR (Aero URL); Native AR (Android, iOS)	Native AR (Android, iOS), AR headset (Meta Quest Pro)
1. Tracking capabilities	1. Fiducial tracking		X				X (VuMark)				No info	N/A	N/A	N/A	N/A	N/A		
	2. Image tracking	X	X	X	X	X	X (Image, cylinder, multi targets)		X	X	No info	N/A	N/A	N/A	N/A	N/A	X (Image anchor)	X (target tracking)
	3. Face tracking	X			X				X	X	No info	N/A	N/A	N/A	N/A	N/A		X
	4. Location tracking		X		X	X			X	X	No info	N/A	N/A	N/A	N/A	N/A		
	5. Object tracking						X (Model targets)			X (Physical objects)	No info	N/A	N/A	N/A	N/A	N/A		
	6. Surface tracking			X (Hit test)	X	X	X (Ground plane)		X (Hit test)	X (Surface detection)	No info	N/A	N/A	N/A	N/A	N/A	X (Surface anchor)	X (plane tracking)

Appendix: AR Dev. Tool Suitability Decision Matrix 2/3

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by:
1) Tracking capabilities 2) Rendering capabilities 3) Ease of development 4) Licensing cost

Tracking engine	Rendering engine	Tracking + Rendering

	Selection Criteria (SC)	MindAR	AR.js	WebXR	8th Wall	Lightship ARDK (2021)	Vuforia (2011)	Azure Spatial Anchors	ARCore (2018)	ARKit (2017)	Manifest (2017)	Three.js	A-frame	Unity	Unreal	RealityKit	Adobe Aero (2019)	Meta Spark Studio (2017)
1. Tracking capabilities	7. Spatial tracking					X	X (Area targets)	X (Spatial anchors)			No info	N/A	N/A	N/A	N/A	N/A		
	8. Other tracking									Body tracking;	No info	N/A	N/A	N/A	N/A	N/A		Iris tracking; body tracking; Hand tracking;
	9. Multi-marker tracking	X	X		X (image tracking)		X		X (image tracking)	X (image tracking)	No info	N/A	N/A	N/A	N/A	N/A		X (image tracking; plane tracking)
	10. Multi-user AR session			Possible with tools like Wrapper.js		X	X (Vuforia Chalk remote assist)	X	X (Cloud anchors)	X	No info	N/A	N/A	N/A	N/A	N/A		
	11. Depth tracking			X		X			X	X	No info	N/A	N/A	N/A	N/A	N/A		
	12. Lighting effects			Light estimate;	Light estimate;	Light estimate;				Light estimate; realistic reflection;	No info	N/A	N/A	N/A	N/A	N/A		

Appendix: AR Dev. Tool Suitability Decision Matrix 3/3

Selection criteria for AR platforms (web AR vs. native AR vs. AR-on-headset) are categorized by:
1) Tracking capabilities 2) Rendering capabilities 3) Ease of development 4) Licensing cost

Tracking engine	Rendering engine	Tracking + Rendering

	Selection Criteria (SC)	MindAR	AR.js	WebXR	8th Wall	Lightship ARDK (2021)	Vuforia (2011)	Azure Spatial Anchors	ARCore (2018)	ARKit (2017)	Manifest (2017)	Three.js	A-frame	Unity	Unreal	RealityKit	Adobe Aero (2019)	Meta Spark Studio (2017)
2. Rendering engine	1. Light estimation	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	X (WebXR)	X (WebXR)	X (ARCore, ARKit)	X (ARCore; ARKit)	X (ARKit)		
	2. Occlusion	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A			X (ARCore, ARKit)	X (ARCore;ARKit)	X (ARKit)		
3. Ease of develop-ment	1. Integration with other AR dev. tools	Three.js; A-frame;	Three.js; A-frame;	Three.js; A-frame;	Three.js; A-frame;	Unity;	MRTK; Magic Leap OS; ARCore/ ARKit;	Unity; ARCore;	Vuforia; Unity; Unreal; WebXR;	Vuforia; Unity; Unreal;	Unity;	WebXR;	WebXR;	OpenXR; MRTK; ARCore; ARKit;	OpenXR; MRTK; ARCore; ARKit;	ARKit		
	2. Simulation/ remote testing			X (WebXR API Emulator)		X (Mock mode)	X (Play mode)		X (Android emulator)		No info			X (AR Foundation Remote for ARCore+ARKit)	X (In-editor testing)			X (simulator)
	3. Low-code/ no-code development						X (Vuforia Chalk, Expert Capture, Instruct, Studio)				X (Manifest Maker)						X	X
4. Licensing cost	1. Open-source	X	X	X								X	X					