A Mixed Reality Interface for Digital Twin Based Crane

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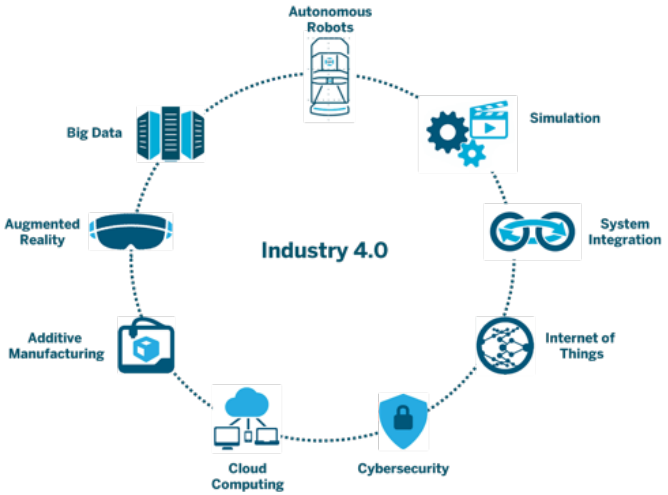
8th April 2021

Mechatronic Circus & Demo day

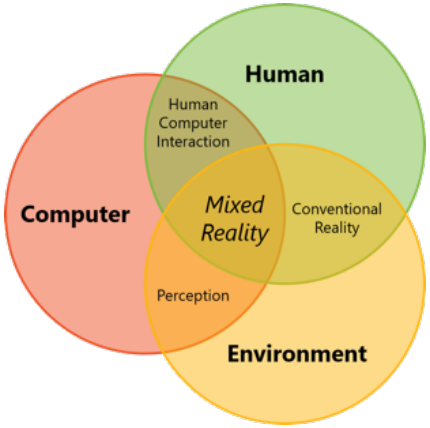
Parallel session: “Digital twin interfaces; HMI and data processing”

Background

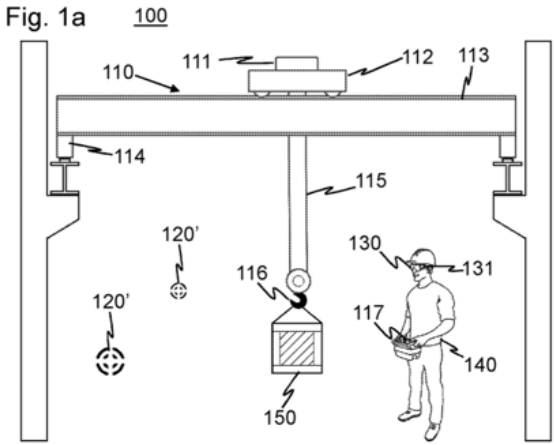
Industry 4.0, HMI, mixed reality, and crane application

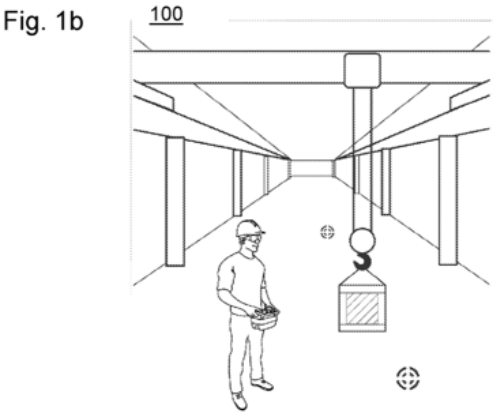


Nine Technologies Transforming Industrial Production [1]



Human-Computer-Environment Interactions [2]



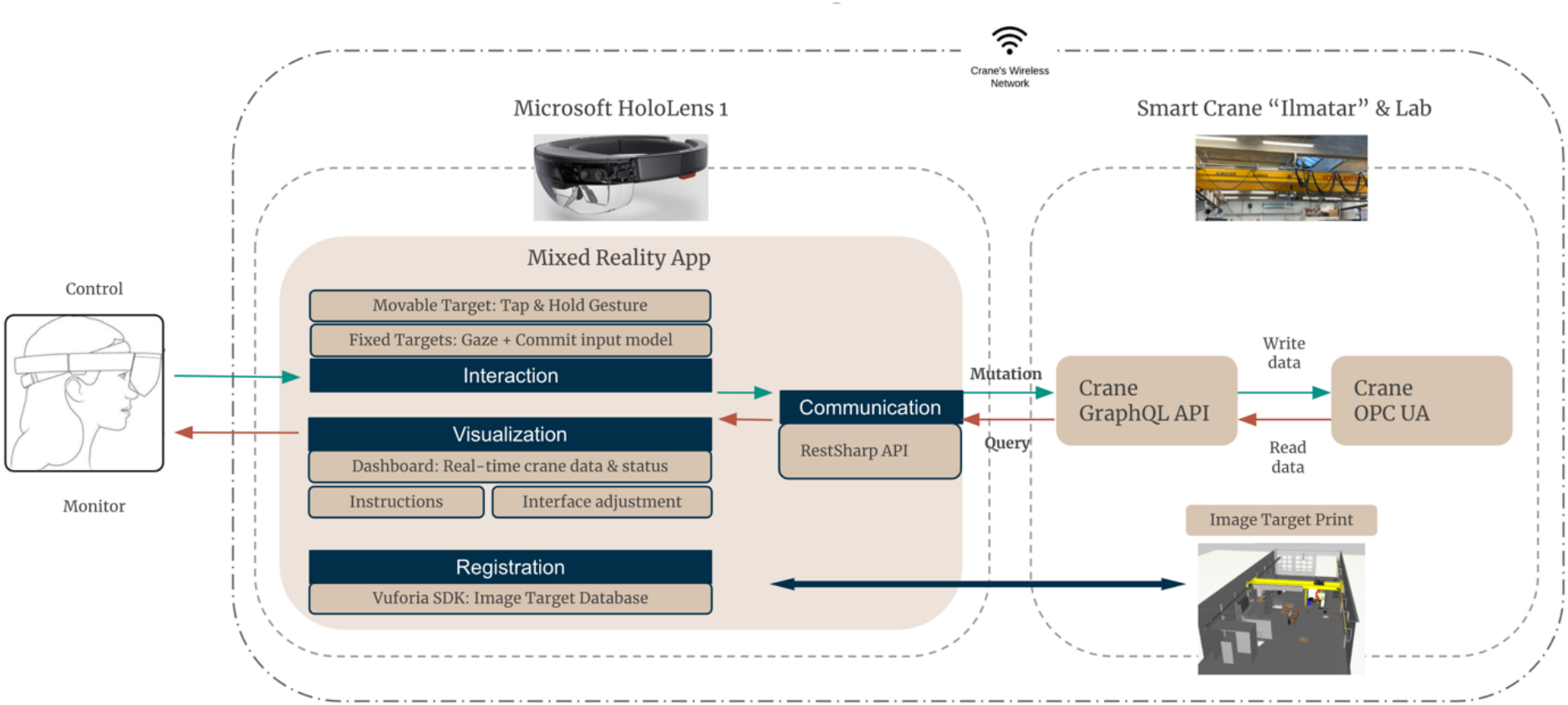


Reality-Virtuality (RV) Continuum [3]

Controlling of Lifting Device (Konecranes) [4]

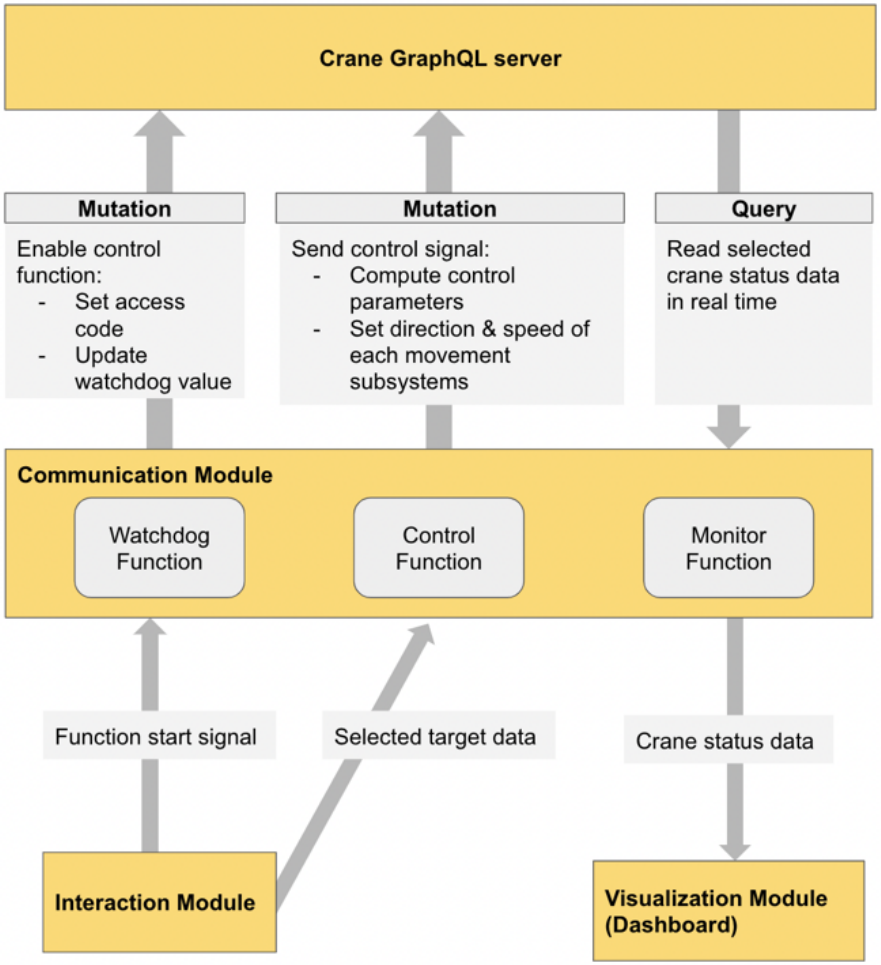
Prototype setup, architecture and workflow

Modularized design of the mixed reality application for crane “Ilmatar”



Communication as a key for data-driven HMI

Dataflow within the application, as well as between the interface and the crane



The **communication module** functions as a bridge between the crane and all the other modules in the MR application prototype.

Accessing the crane data, and further:

- displaying it in the dashboard of the visualization module; or
- modifying it in the target control of the interaction module.

Behind the scene:

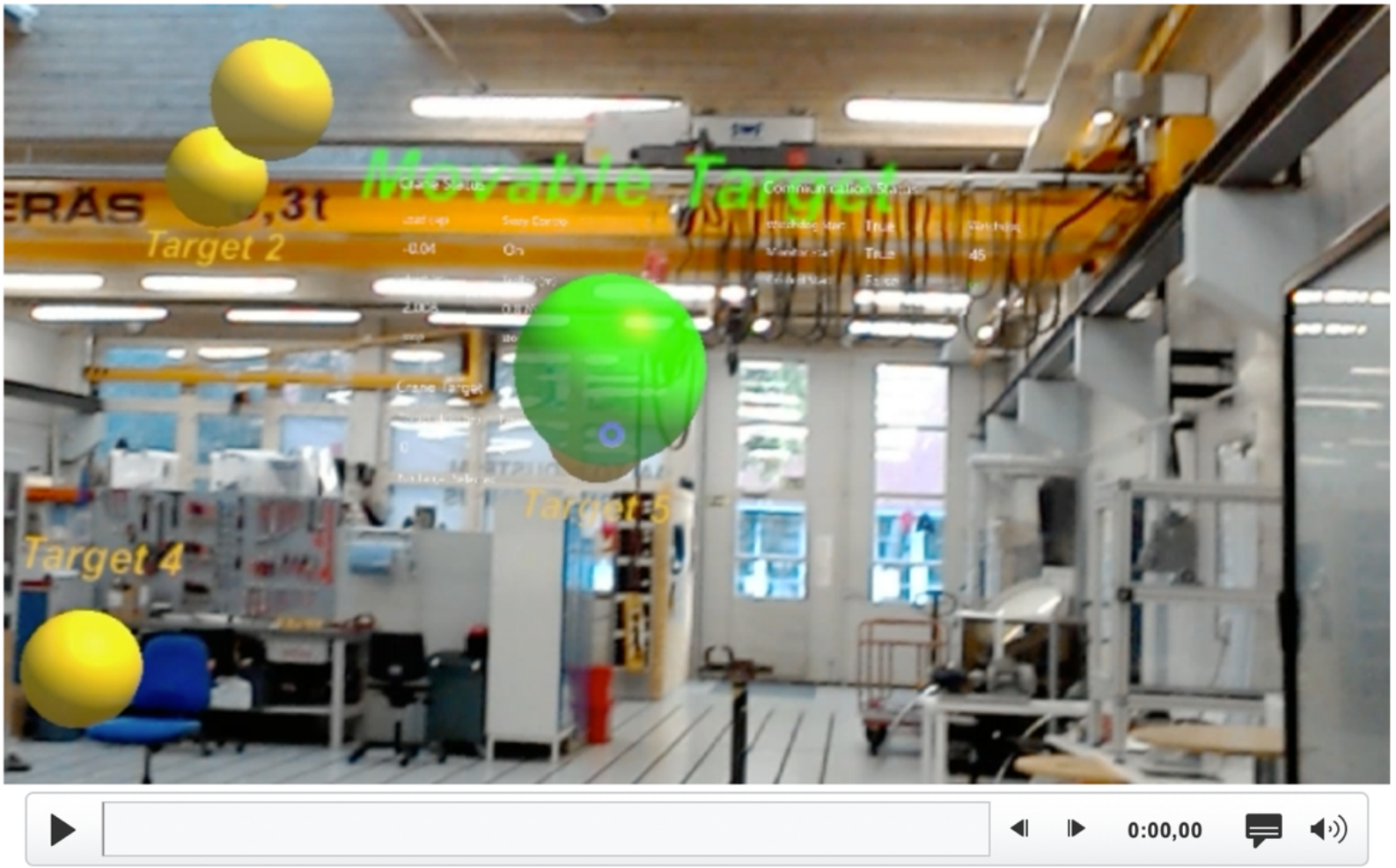
- Leveraging the **RestSharp API** to send HTTP request (either query to read data, or mutation to write data) to the **crane GraphQL wrapper;**
- Multi-threaded vs. single thread behaviour:
  - Watchdog function;
  - Monitor function;
  - Control function.
- Determining request frequency, size and timeout

Demo

HoloLens device portal capture: instruction phase

Demo

HoloLens device portal capture: registration, visualization, interaction phases



List of References

[1] T. Melanson. What Industry 4.0 Means for Manufacturers. *Blog, Blog AP, Blog EU, Robotics.* URL https://aethon.com/mobile-robots-and-industry4-0/

[2] M. Speicher, B. D. Hall, and M. Nebeling. What is mixed reality? In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, CHI '19, page 1–15, New York, NY, USA, 2019. Association for Computing Machinery. ISBN 9781450359702. doi: 10.1145/3290605.3300767. URL https://doi.org/10.1145/3290605.3300767.

[3] P. Milgram, H. Takemura, A. Utsumi, and F. Kishino. Augmented reality: a class of displays on the reality-virtuality continuum. *Telemanipulator and Telepresence Technologies*, 2351(December 2013):282–292, 1995.

[4] Rantala et al. Konecranes Global Oy. Controling of lifting device, 2019. United States Patent. US10495880B2. URL https://patents.google.com/patent/US10495880B2/en?oq=US+10%2c495%2c880+B2

Thanks for your attention.

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Backup Slides for Q&A

Related Work & Existing Solutions

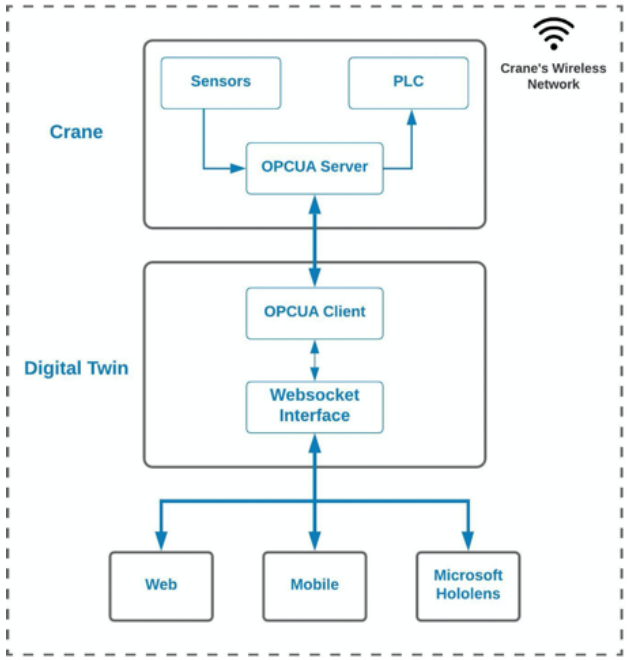
Existing Solutions on smart crane operation HMI

HoloLens app as part of digital twin prototype: [10]

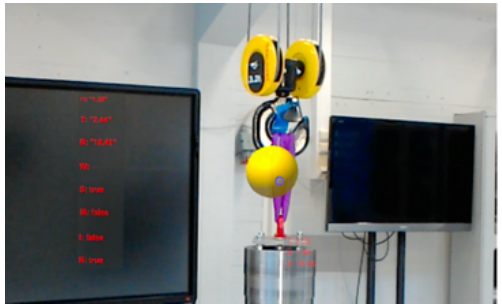
- voice/gesture/gaze input to control crane with fixed hologram points;
- a fixed viewfinder to display crane status;
- communication with OPC UA through WebSocket API and Express Node framework (obsolete);
- restricted flexibility/mobility of user when initializing the app

Web-based user interface with GraphQL: [11]

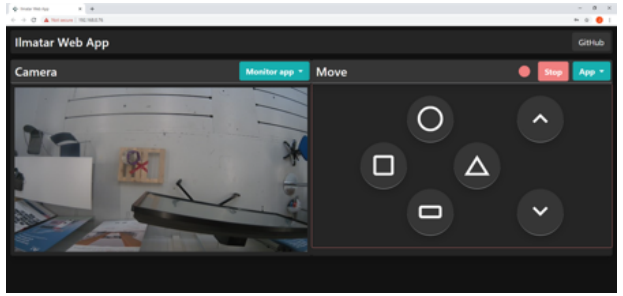
- Monitor crane variables and IP-camera
- Control movement of each subsystems



Digital Twin prototype reference architecture [10]



HoloCrane App. Crane moved to target [10]



Interface of "Ilmatar" Web App with GraphQL [11]

Hardware Setup

Microsoft HoloLens (1st generation) - device specifications [12]

Display

Optics	See-through holographic lenses (waveguides)
Holographic resolution	2 HD 16:9 light engines producing 2.3M total light points
Holographic density	>2.5k radiants (light points per radian)
Eye-based rendering	Automatic pupillary distance calibration

Sensors

- 1 inertial measurement unit (IMU)
- 4 environment understanding cameras
- 1 depth camera
- 1 2MP photo / HD video camera
- Mixed reality capture
- 4 microphones
- 1 ambient light sensor

Processors

- Intel 32-bit architecture with TPM 2.0 support
- Custom-built Microsoft Holographic Processing Unit (HPU 1.0)

Power

- Battery Life
- 2-3 hours of active use
- Up to 2 weeks of standby time
- Fully functional when charging
- Passively cooled (no fans)

Memory

- 64 GB Flash
- 2 GB RAM

Input, output, and connectivity

- Built-in speakers
- Audio 3.5mm jack
- Volume up/down
- Brightness up/down
- Power button
- Battery status LEDs
- Wi-Fi 802.11ac
- Micro USB 2.0
- Bluetooth 4.1 LE

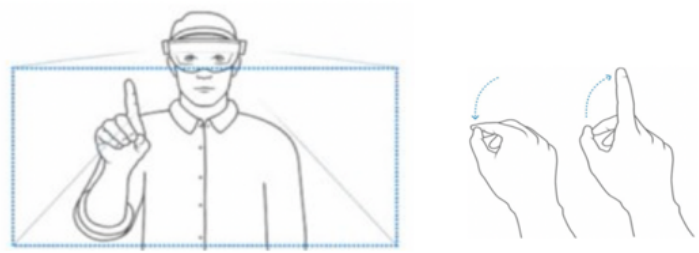
Hardware Setup

Microsoft HoloLens (1st generation) - device capabilities [12]

1. Gaze Tracking

- Navigate the cursor
- HoloLens 1 only support Head-gaze, no Eye-gaze

2. Gesture Input



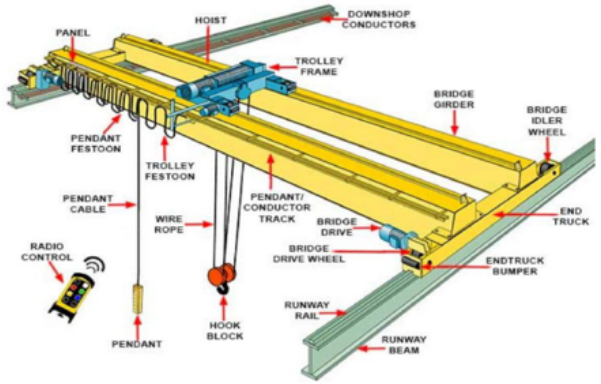
- Air Tap: select; Bloom: start/close menu; Tap and Hold: click and drag, .etc
- HoloLens 1 only support simple interaction, no complex gesture recognition for manipulation

3. Voice Support

- Speech commands
- Hand-free mode

Hardware Setup

Smart crane “Ilmatar” & AIIC



Crane Component Overview [13]

Subsystem	Feature	Value
Hoist	Lifting Height	3 meters
	Lifting Speed	8 meters/ minute
	Lifting Capacity	3200 kg
Trolley	Moving Range	9 meters
	Moving Speed	20 meters/ minute stepless
Bridge	Moving Range	9 meters
	Moving Speed	20 meters/ minute stepless

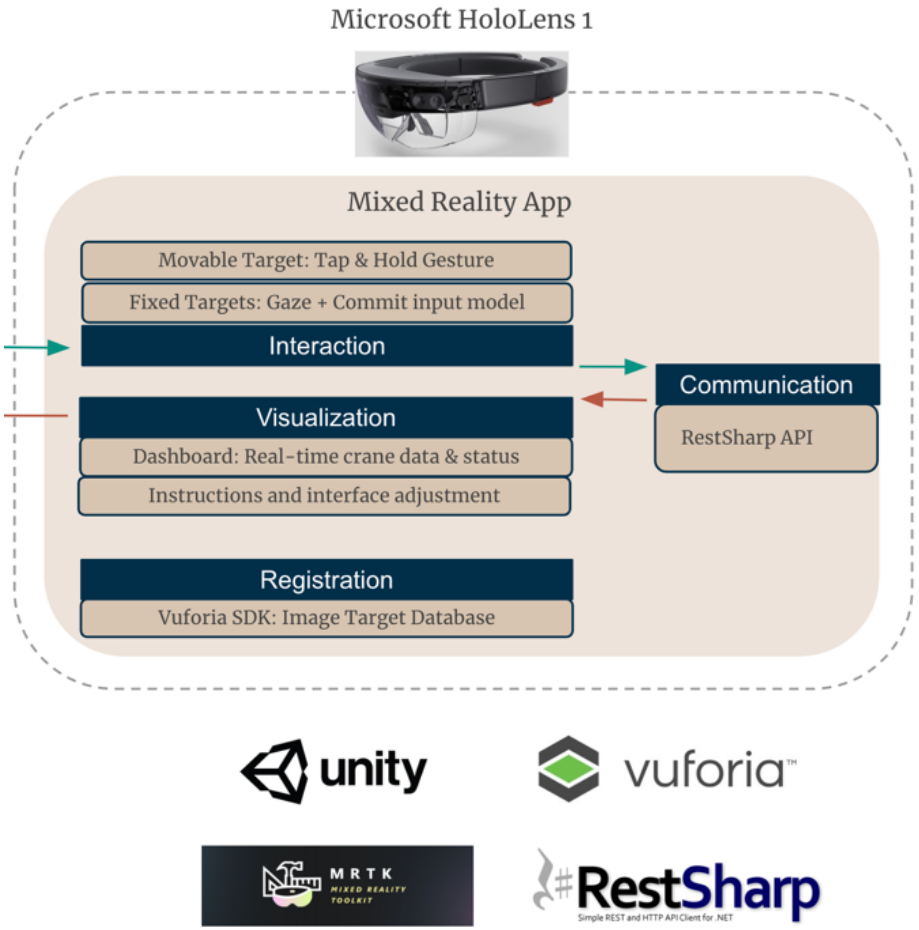
Crane Movement Subsystems [13]

Crane Side Look [10]

Crane and AIIC Visual Component Model – Look 1, 2 [14]

Software Setup

Software and toolkit for mixed reality application development



- **Unity3D engine:** main platform for MR app development of all modules
- **Microsoft Mixed Reality Toolkit (MRTK):** supporting MR input system and interactive components for interaction and visualization modules
- **PTC Vuforia AR SDK:** registering space and (extended) tracking device for registration module
- **RestSharp API:** sending HTTP request to GraphQL for communication module
- **Task Parallel Library (TPL) in .NET framework:** multi-threaded behaviour for communication module

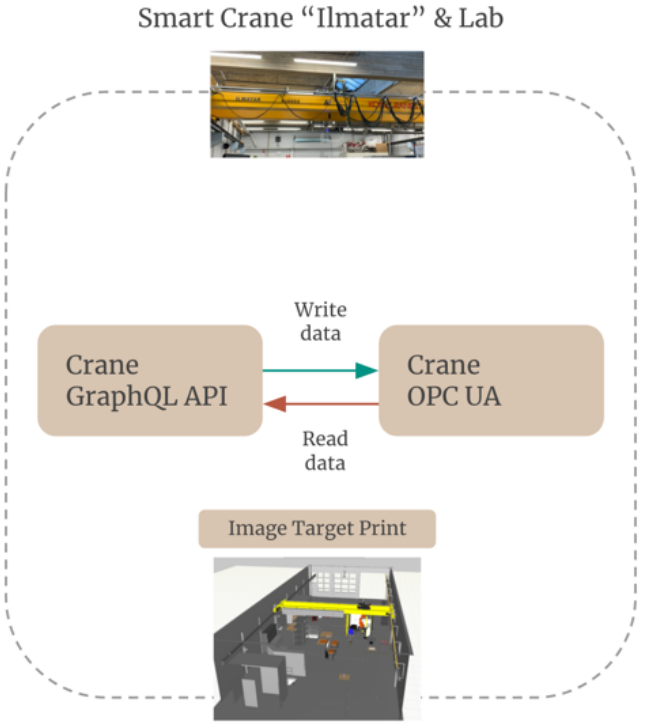
Software Setup

Software systems and connectivity of the crane

- **Crane software systems**
  - Crane OPC UA interface and data access
  - Crane GraphQL wrapper
- **Crane connectivity**

Software System	Purpose	Location
PLC	Handle crane's sensor data and control system.	Crane
OPC UA Server	Provides external access to crane data and controls (hoist, bridge, trolley)	Crane
Remote Controller System Software	Enables external control of the crane.	External Equipment
UI Server	Provides external access to the web UI.	Crane
Remote Monitoring System	Provides external access for monitoring.	Crane

Crane Software Systems Overview (2018)



Software Setup

Crane OPC UA interface & data access

Variable name (prepend SCF.PLC.DX_Custom_V.Controls.)	Data type	Description
Watchdog	Int (16bit)	Has to change constantly
AccessCode	DInt (32bit)	Personal Access code
Hoist.Up	Bool	1 = Up / Position increases
Hoist.Down	Bool	1 = Down
Hoist.Speed	Float (32bit)	0 - 100 % / Maximum speed is limited by the PLC SW
Trolley.Forward	Bool	1 = Forward / Position increases
Trolley.Backward	Bool	1 = Backward
Trolley.Speed	Float (32bit)	0 - 100 % / Maximum speed is limited by the PLC SW
Bridge.Forward	Bool	1 = Forward / Position increases
Bridge.Backward	Bool	1 = Backward
Bridge.Speed	Float (32bit)	0 - 100 % / Maximum speed is limited by the PLC SW

Control Variables – Manual Control [15]

Variable name (prepend SCF.PLC.DX_Custom_V.Controls.TargetPositioning)	Data type	Description
SelectionInUse	Bool	1 = Target Selection from OPC UA
DriveToTarget	Bool	1 = Drive to Target
DriveToHome	Bool	1 = Drive to Home Target
Target	Int (16bit)	Target Positioning target number, [1..200], 0= No target selected
Home	Int (16bit)	Target Positioning home target number, [1..200], 0= No target selected

Control Variables – Target Positioning Control [15]

Variable name (prepend SCF.PLC.DX_Custom_V.Status.)	Data Type	Description
ReadingControls	Bool	1 = Controls are read from OPC interface
WatchDogFault	Bool	1 = Watchdog fault active / Watchdog value is not changing

Control Variables – Control Status [15]

Variable name (prepend SCF.PLC. DX_Custom_V. RadioSelection)	Data type	Description
Inching	Bool	1 = Inching is activated from radio controller
MicroSpeed	Bool	1 = MicroSpeed is activated from radio controller
RopeAngleFeaturesBypass	Bool	1 = Rope Angle Feature Bypass is activated from radio controller
SwayControl	Bool	1 = Sway Control is activated from radio controller
SwayControl_SlingLength_mm	DInt (32bit)	Sway Control Sling length selection in millimeters.

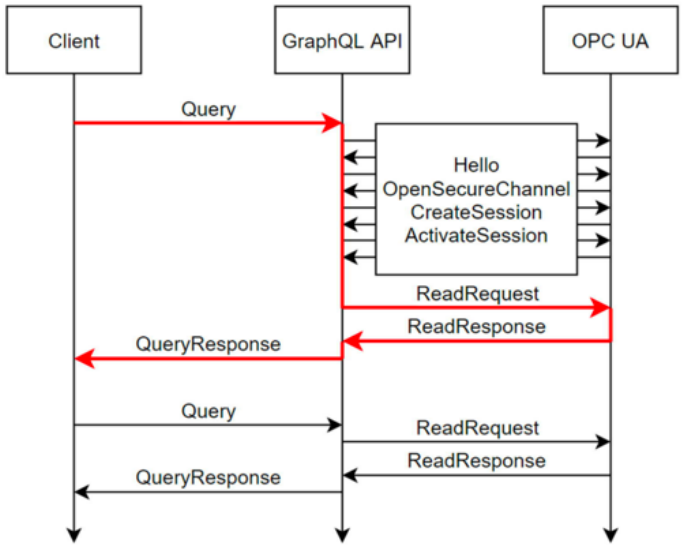
Variables (Read) – Radio Selection [16]

Variable name (prepend SCF.PLC.DX_Custom_V.Status.Hoist)	Data type	Description
Diagnostics.Ok	Bool	1 = Machinery OK
Diagnostics.Event_Active	Bool	1 = At least one event is active
Diagnostics.Alarm_Active	Bool	1 = At least one alarm is active
Diagnostics.Fault_Active	Bool	1 = At least one fault is active
Diagnostics.Bypass_Active	Bool	1 = At least one bypass is active
ControlSignals.Direction1_Request	Bool	1 = Driving command on from active control place (Up / Forward)
ControlSignals.Direction2_Request	Bool	1 = Driving command on from active control place (Down / Backward)
ControlSignals.Speed_Request	Float (32bit)	Speed Reference in % from active control place
ControlSignals.SpeedFeedback	Float (32bit)	Current speed in %
ControlSignals.SpeedFeedback_mmin	Float (32bit)	Current speed in m/min
ControlSignals.MotorTorque	Float (32bit)	Motor Torque %, Positive when motoring and negative when generating
Position.Calibrated	Bool	1 = Position is calibrated
Position.Position_m	Float (32bit)	Current Position in meters
Position.Position_mm	DInt (32bit)	Current Position in millimeters
Position_Raw	DInt (32bit)	Raw position measurement in millimeters
Position.UpStop_m	Float (32bit)	Up stop limit position in meters
Load.Load_t	Float (32bit)	Current gross load in tons
Load.TaredLoad_t	Float (32bit)	Current tared load in tons
Load.GrossLoad_Percentage	Float (32bit)	Current gross load in %
Load.TaredLoad_Percentage	Float (32bit)	Current tared load in %

Variables (Read) – Hoist Machinery [16]

Software Setup

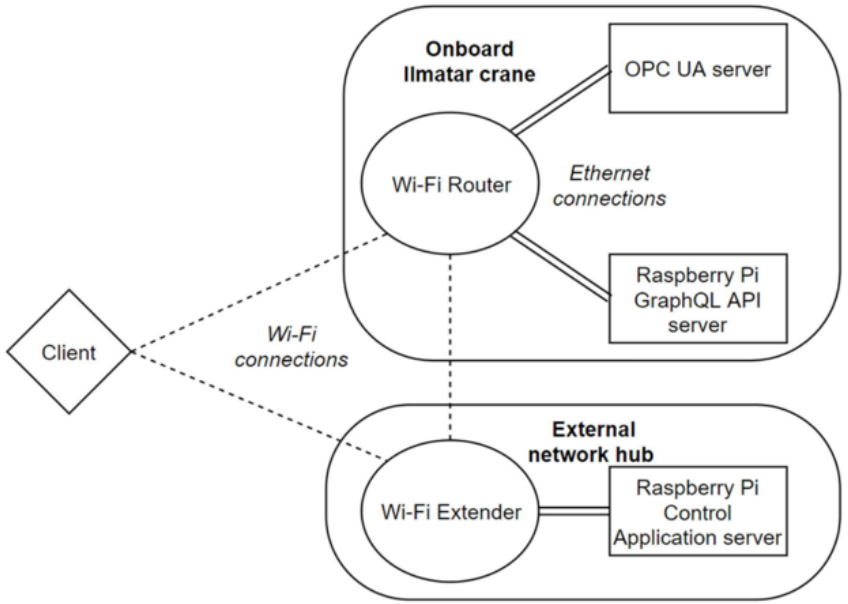
Crane GraphQL wrapper & crane connectivity



Communication Flow with GraphQL Wrapper [11]

Read	Write	Add
DisplayName Description Variable • DataValue • DataType • SourceTimestamp • Statuscode NodeId Child nodes	DataValue Description	Folder node Variable node

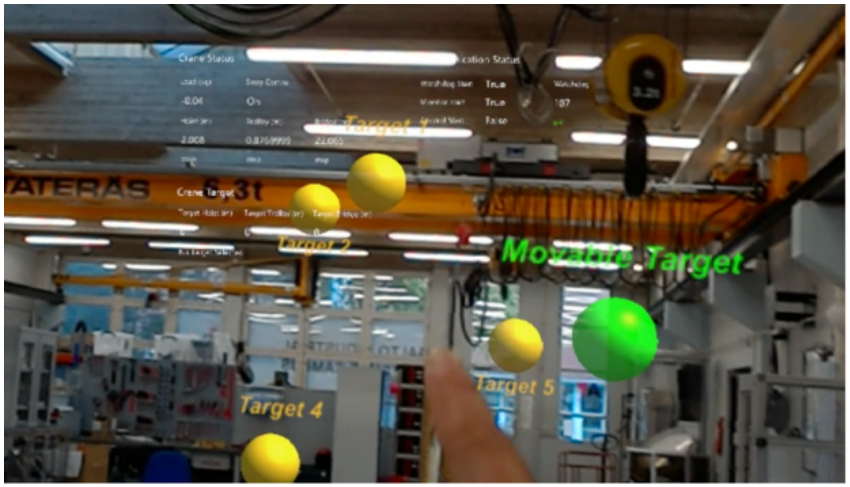
OPC UA GraphQL Wrapper Operation Node [11]



Crane Connectivity and Network [11]

Prototypical Development

Interaction module



HoloLens View Before Interaction

HoloLens View During Movable Target Control (with Spatial Mapping)

The **interaction module** enables the control of crane through interacting with the virtual balls in the scene.

There are two ways of control.

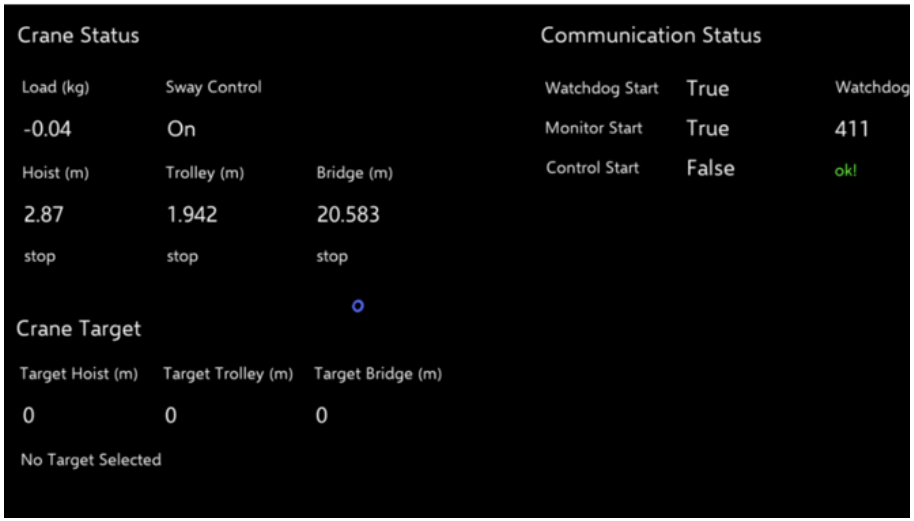
- **Fixed target control**: gaze and air-tap to select a fixed target;
- **Movable target control:** gaze, tap and hold to navigate and place the movable target

Behind the scene:

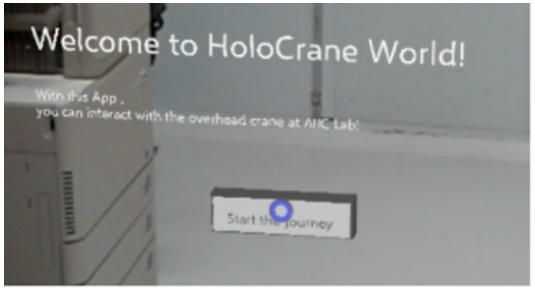
- Interaction enabled by Input system of MRTK;
- Constantly computing difference between the crane current position (from communication module) and selected target position, and moving each sub systems accordingly (first trolley/bridge forward/backward, then hoist up/down);
- Pre-calculating the offset of transformation between Unity scene and crane coordinate

Prototypical Development

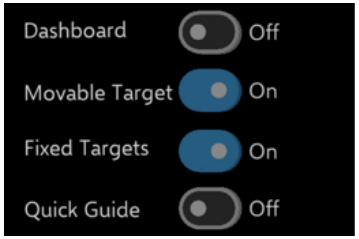
Visualization module



Dashboard in Unity Scene



Instruction in HoloLens View



Interface Adjustment in Unity Scene

The **visualization module** enables the users to:

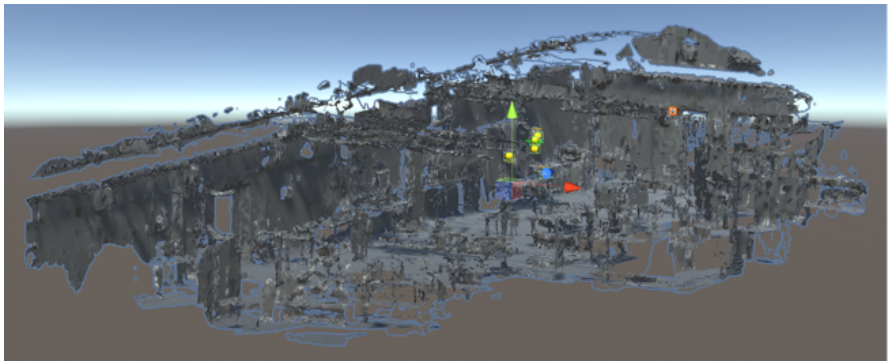
- directly monitor the crane real-time status through a **dashboard;**
- view the **instructions** on how to use the application;
- **adjust the interface** (MR scene) in the way that they prefer through switching on/off the toggles of certain virtual objects.

Behind the scene:

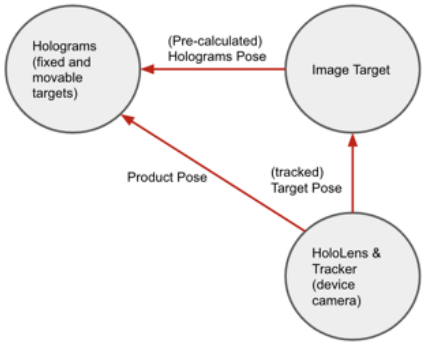
- Interactive UI enabled by prefab components from Unity MRTK
- Dashboard values coming from communication module and interaction module

Prototypical Development

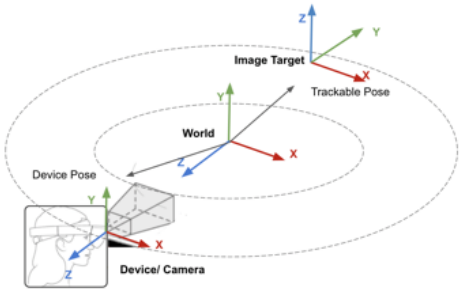
Registration module



Spatial Mapping, Holograms and Image Target in Unity Scene



Full SRG in Registration Module



FOR of World, Device /Camera and Targets

The **registration module** aims at placing the holograms at the pre-defined positions in the physical environment regardless of the user's location when the application is initialized. Only an initial registration action need to be conducted.

Behind the scene:

- Enabled by Vuforia AR SDK in Unity, utilizing its features of image target, device tracking and extended tracking;
- Applying the spatial relationship graph (SRG) and frame of reference (FOR)
- Calibrating image target database and holograms positions with spatial mapping mesh

Image Target with Bounding Box in HoloLens View

Evaluation on Control Accuracy

Evaluation procedure

1. **Collecting evaluation data**
   - After registration, we select a target in the HoloLens scene;
   - Manually navigate the crane with the remote controller to the selected target, where the crane hook is aligned with the hologram of the target;
   - Read the target positions P_{target} (predicted value) and the crane status positions P_{status} (observed value) of the three subsystems from the hologram dashboard;
   - Repeat the above step for
     - Fixed Target Control: 3 experiments, 12 test sets
     - Movable Target Control: 10 experiments / test sets

2. **Calculating the Root Mean Square Error (RMSE)**

$$RMSE = \sqrt{\frac{\Sigma_{i=1}^{n}(P_{target} - P_{status})^2}{n}}$$

3. **Visualizing with Error Ellipsoid**
   - Algorithm for minimum volume covering ellipsoid (MVEE)
   - Plot with python matplotlib library

Evaluation on Control Accuracy

Data collection and RMSE calculation

Fixed Target Control														
	Test 1				Test 2				Test 3					
Target position	1	2	4	5	1	2	4	5	1	2	4	5		
B	20,684	20,04	20,523	20,04	20,684	20,04	20,523	20,04	20,684	20,04	20,523	20,04		
H	2,021	2,021	1,055	1,538	2,021	2,021	1,055	1,538	2,021	2,021	1,055	1,538		
T	1,561	1,883	1,883	1,078	1,561	1,883	1,883	1,078	1,561	1,883	1,883	1,078		
Status position	1	2	4	5	1	2	4	5	1	2	4	5		
B	20,703	20,06	20,533	20,066	20,765	19,998	20,606	20,099	20,778	20,196	20,51	20,025		
H	2,024	2,024	1,073	1,529	2,015	1,992	1,074	1,53	2,005	1,99	1,049	1,527		
T	1,583	1,914	1,906	1,112	1,596	1,91	1,926	1,12	1,602	1,959	1,951	1,142		
Difference	1	2	4	5	1	2	4	5	1	2	4	5		RMSE
B	-0,019	-0,02	-0,01	-0,026	-0,081	0,042	-0,083	-0,059	-0,094	-0,156	0,013	0,015	Bridge	0,05508251
H	-0,003	-0,003	-0,018	0,009	0,006	0,029	-0,019	0,008	0,016	0,031	0,006	0,011	Hoist	0,01607016
T	-0,022	-0,031	-0,023	-0,034	-0,035	-0,027	-0,043	-0,042	-0,041	-0,076	-0,068	-0,064	Trolly	0,04552838

Fixed Target Control: 3 experiments, 12 test sets

Movale Target Control													
Target position	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10			
B	21,367	20,771	20,85	21,177	21,927	21,748	21,181	21,535	22,176	22,383			
H	0,854	1,171	1,316	1,628	1,523	1,765	1,317	1,413	1,32	2,312			
T	1,065	1,889	1,424	1,855	1,448	2,259	2,683	2,701	2,19	1,472			
Status position	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10			
B	21,394	20,871	20,943	21,308	21,924	21,72	21,15	21,513	22,131	22,461			
H	0,86	1,187	1,322	1,628	1,522	1,755	1,317	1,427	1,344	2,256			
T	1,131	1,942	1,466	1,913	1,483	2,321	2,749	2,765	2,243	1,467			
Difference	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9	Test 10			RMSE
B	-0,027	-0,1	-0,093	-0,131	0,003	0,028	0,031	0,022	0,045	-0,078		Bridge	0,06847335
H	-0,006	-0,016	-0,006	0	0,001	0,01	0	-0,014	-0,024	0,056		Hoist	0,02082547
T	-0,066	-0,053	-0,042	-0,058	-0,035	-0,062	-0,066	-0,064	-0,053	0,005		Trolly	0,05352383

Movable Target Control: 10 experiments / test sets

RMSE range: 1cm - 7cm
Pattern: hoist < trolley < bridge

Suggested Future Work