Unified framework for mixed-reality assisted situational adaptive robotic path planning enabled by 5G networks for deconstruction tasks

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Abstract –

The development of 5G networks is expected to accelerate the realization of Industry 4.0 with its extended capabilities such as network slicing, reduced latency, increased bandwidth and much more. Leveraging these improved network performances, real time machine to machine communication could be realized. Moreover, in situations where human-machine interactions take place, safety protocols and systems can also be revisited and enhanced. In this paper, a unified framework between ROS, a widely adopted robotic middleware, and Unity, a versatile game development engine is developed. The system utilizes ROS' adaptability to operate robots, while Unity offers a visually engaging user interface. Through this unified approach, industrial mobile communication between machines and human operators is elevated, allowing for efficient coordination and synchronization of robotic tasks during complex deconstruction processes. Thus, increasing safety on construction sites on the one hand and improving general working conditions on the other.

Keywords –

5G network; Unity; ROS; Human-machine interaction; deconstruction

1 Introduction

In construction projects, on-site workers face significant occupational hazards. Workers in this industry are more susceptible to injuries and accidents compared to those in other industries, as highlighted by German Social Accident Insurance on the yearly report of 2022 [1]. Even within the construction industry, deconstruction processes are among the more dangerous processes due to unforeseeable scenarios such as unnoticed loosened building elements, unpredictable cracks and are therefore hazardous in more ways than one. This risk is especially pronounced during the deconstruction process, where deformation, cracks, and falling building elements are among the factors that may lead to unforeseeable accidents. Furthermore, there are pollutants such as silica dust [2] and building element particles [3] present during the construction and deconstruction processes. In which long-term exposure to these substances can have serious negative effects on the health of the workers. One improvement suggestion to this is to reduce the working time of construction workers on the site, particularly during critical processes.

In recent years, in an effort to reduce exposure of workers to highly hazardous processes, researches on teleoperation and remote controlling have been an increasingly popular theme especially in the field of deconstruction robotics [4]. In the context of research field, Robot Operating System (ROS2) [5] is one of the more popular frameworks in developing robotic applications for teleoperation as shown in following papers [6] [7].

However, this approach could be further enhanced by integrating it with Unity [8], a multifaceted game development platform. By adopting this consolidated framework, a more inclusive and customised user experience can be provided as Unity supports multiple protocols, including Message Queuing Telemetry Transport, (MQTT) [9], and enables the creation of mixed reality applications for an even more intuitive and immersive path planning and control [10]. With the implementation of a mixed reality functionality, the remote operator would have an enhanced situational awareness along with increased engagement and focus.

The use of ROS2 in conjunction with Unity is an established research direction explored in a number of comparative studies [11] [12]. These studies compare different simulation environments for vehicle control within different virtual simulation environments such as Unity, V-Rep [13], and Gazebo [14]. Additionally, such a framework has been adopted into industrial robotic process monitoring [15], and unmanned underwater vehicle simulation for telepresence robots [16]. In this particular research paper, the connection between ROS2 nodes and TCP connection with Unity is established. The Unity-developed application functions as the user interface for visualization and path planning, with messages forwarded to ROS2 for device control and processing.

However, most related research was conducted in controlled environments or virtual world, which stands in contrast to the construction site's highly dynamic nature, making it susceptible to unexpected events. Therefore, the aim of this paper is to address the research question: "How can a unified framework of ROS and Unity be implemented for construction to improve communication and aid robotic planning for on-site deconstruction tasks through 5G network ?"

1.1 Potential

The integration of Unity in ROS2 involves many intricate steps. Yet, the possibility for visualization and control is highly enhanced. Unity's interoperability with MQTT, a popular IoT communication standard [17], enables it to control devices using different communication protocols. This allows for complete control from a single application. Since this matches the nature of construction sites where stakeholders commonly change throughout the construction project and each one contributes their individual solutions for communication, the potential in streamlining communication between the stakeholders by a unified framework is remarkable.

Furthermore, there is an increasing potential and deployment of semi- and fully-autonomous machines such as Autonomous Guided Vehicles (AGVs) on the construction sites to assist with heavy duty processes [18]. These AGVs, can be equipped with GPS trackers that can communicate via MQTT to enable accurate real-time location display on a deconstruction site. Operators may now carefully arrange the actions of the deconstruction robot provided with this information.

In addition, Unity, being a prominent development engine for Mixed Reality applications, offering expansive potential for Virtual Reality (VR) and Augmented Reality (AR), this use case can be extended as a standalone AR application using Unity. One of the major potentials of mixed reality is the amalgamation of virtual environment with the physical one, providing visual cues from both side of the environment, allowing the user to more informed and better decisions. This is especially relevant for deconstruction, where in contrast to traditional demolition, where materials and building elements are to be recovered. Thus, any damage to the materials and building elements whilst deconstruction operation is to be minimised. Besides that, during the machine operation, danger zones could also be defined to trigger responsive actions, prompting the motion of the machines to slow down or halt instantly upon the detection of any risks. The risks could include any humans or machines that enter the defined danger zones. This integrated framework showcases the versatility of Unity and ROS in orchestrating seamless communication, offering practical solutions for complex industrial scenarios such as construction sites.

Due to the transitory nature of the construction site, machines and workers are constantly moving around. A robust, stable and real time network is needed for the communication between the machines. The requirements for safety protocols are insufficient with the current WLAN performance [19]. An extensive research on the overview of Extended Reality (XR) in mobile networks, it is shown that 4G network is unable to provide the latency and uplink/downlink capacity for the necessary use cases [37].This is where 5G networking comes into play, where the technical requirements for 5G networks are as described by 3GPP in this technical specification [20]. These requirements allow for a real-time safety and control communication protocol between human-machine and machine-machine.

2 Methods and implementations

The described and implemented use scenario originates from a use case for 5G enabled and mixed reality supported deconstruction planning developed in TARGET-X research project [21]. In the project 5G is being introduced as new wireless communication standard into key industries like construction and its performance is evaluated in large scale trials such as the 5G Industry Campus Europe (5G-ICE) at Campus Melaten Aachen [22].

2.1 Experimental Setup

In order to test the planned setup including equipment, processes and technology within the 5G network ecosystem, the Reference Construction Site in Aachen is utilized. The Reference Construction Site is a test bed that is officiated by the Center Construction Robotics. It serves as living lab for research in construction by simulating an actual construction site with real processes while still providing a controlled environment.

Moreover, for this test bed, a 5G network infrastructure has been developed in which the tower crane on the Reference Construction Site plays the role as a transmission tower to provide the site with a 5G network [23]. The tower crane was chosen because it is positioned centrally on the site and allows for elevated mounting of the antennas. Additionally, omni-antennas were installed such that any rotational maneuvers of the crane during construction does not affect the network coverage. Hence, the developed 5G network infrastructure is able to reflect that construction sites are typically dynamic in terms of resource and spatial availability.

Figure 1. Construction Site operated by Center Construction Robotics in Aachen.

3 Implementation in Unity

For the setup of the unified framework, there are multiple software assets and packages that are used. These packages include assets from Unity:

- **ROS-TCP-Connector** [24] is responsible for the connection between ROS and Unity, this package is based on a previous from ROS#. A TCP endpoint that enables message transfer between Unity and ROS while operating as a ROS node is set up. It also generates C# classes, serializing and deserializing the messages from ROS.
- **Unity Robotics Visualization** [25] allows Unity to visualize incoming and outgoing messages, including navigation messages, sensor data, and more. Messages such as /tf [26] can be visualized as joints in Unity Editor.
- **URDF importer** [27] is used to import a URDF-formatted robot into a Unity scenario. The geometry, graphic meshes, kinematic and dynamic properties of a robot are defined by the URDF file. This package parses a URDF file and imports it into Unity with the help of PhyX 4.0 articulation bodies.
- **BioIK** [28] is an optimized inverse kinematic algorithm solver based on this research paper [29] that can be implemented in Unity directly onto a hierarchical object, including URDF files.
- **Bézier Path Creator** [30] is an asset in Unity that allows user to create paths in Unity dynamically and visualize them during runtime.
- **Vuforia Engine** [31] is an asset in Unity that allows developer to develop their application into Augmented Reality application using anchoring methods such as plane detection, image recognition and object detection.

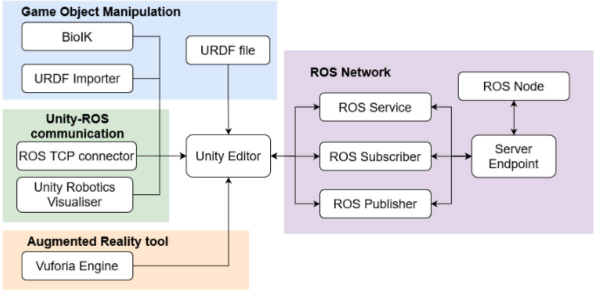

Figure 2. An overview of the categorized functionalities of the packages in Unity

3.1.1 Scene in Unity

The implementation of the packages into the Unity scene are comprised of the following steps:

1. The URDF importer is added into Unity and the URDF file of the robot model is adapted and imported into the scene. The robot is assumed to be stationary as the robot's base does not move during the operational task. In this scenario, a demolition robot, as shown in Figure 3, a BROKK 170 is used.

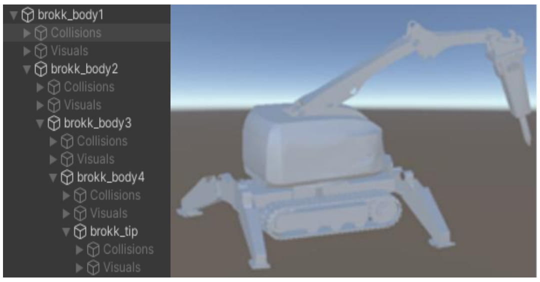

Figure 3. Screenshot of the imported URDF Brokk model.

2. After the model has been imported, inverse kinematics are implemented into the model. In this paper, the BioIK algorithm is deployed. The rotational limits of the joints are defined true to the physical robot's limitation and also to prevent any self-collision. The hierarchical order of the robotic arm is as follow: brokk_base, brokk_body1, brokk_body2, brokk_body3, brokk_boyd4, brokk_tip.
3. Then a target that defines the end position is added into the scene as well. This is necessary to realize the path planning. Using Bézier path creator, the target is programmed to follow the path that is created during runtime.
4. A predefined set of waypoints are included into the scene to define the path which the end effector

should follow. These waypoints can be manipulated by the user. The number of waypoints can be added dynamically during runtime, if the paths of the target should be more complicated.

5. At the parent of the robot of the URDF file, the script ROS Transform Tree Publisher from the ROS-TCP-Connector package is added. This script creates a /tf message and stamps them with the time and transform information from Unity and sends them to the ROS2 endpoint.
6. In ROS2, a TCP endpoint package that establishes the connection between Unity and ROS2 is created. The package is run in parallel with Unity, the communication is represented in Figure 2 in the green and purple areas.

3.1.2 Implementation of mixed reality

With the increasing computational power of handheld devices such as tablets and mobile devices, application that requires heavy computational tasks such as the presented one can be build and deployed to any mid-range devices. One of the advantages of a mixed reality is the amalgamation of virtual environment with the physical one, providing visual cues from both side of the environment, allowing the user to make more informed decisions. As Unity is one of the game engines that supports the development for mixed reality application, this use case can be extended as a standalone Augmented-Reality (AR) application. In addition to the aforementioned implementations, Vuforia Augmented Reality SDK is used to develop an AR application for an enhanced visualization and path planning. The implementation for the Augmented-Reality application in Unity is as follows:

1. Firstly, the Vuforia SDK is imported into Unity. An image target is trained and used as an anchor point. The image target is not limited to any markers such as Aruco markers [32]. Any image that is asymmetric and has sufficient feature points is valid as a target.
2. Alternatively, an object target is also trained to detect the particular shape of the object in real world.
3. The unity packages generated from by Vuforia is inserted into Unity and the hierarchical order of the game objects are rearranged with accordance to the SDK's documentation.
4. The virtual camera in the scene is also changed to the physical camera on the device to take in information from the physical world and superimposing 3D models onto the screen of the device.

3.1.3 5G network communication between different machines in different network

In order to exploit the potential of the 5G network that was implemented on the construction site in this use case, the machine-machine communication is set up as shown in Figure 4.

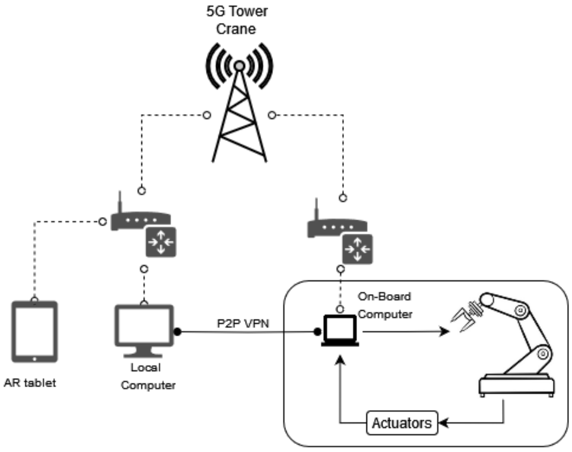

Figure 4. Established connection between multiple machines in the different networks.

The AR application is developed and built as described in section 2.2.1 and 2.2.2, the application is then installed in an Android tablet device. The tablet and a local computer are connected to the same network as shown on the left side of the Figure 4. The /tf messages are sent and received by the local computer.

In order to send ROS messages across different networks in a secure manner, VPN has to be setup. In this case, between the local computer and the on-board computer. A Peer-to-Peer (P2P) tunnel is set up using Husarnet VPN by Husarion. Husarnet uses the ChaCha20-Poly1305 to provide the encryption and authentication of data [33]. With both the machines' IP addresses being added to the peer list, the machines are able to communicate. Cyclone DDS (Data Distribution Service) are installed into both the computers as the recommended middleware in the official documentation from Husarnet. Lastly, the ports on which the ROS2 nodes run, are defined using the ROS_DOMAIN_ID command. In this case, the domain ID is set to be 0. It is necessary to define the domain ID used by DDS to restrict the range of the ports that will be used for discovery and communication. This also means that there can be multiple ROS systems running simultaneously, with an upper limit of 120 processes on one computer. Otherwise, it might spill over into other domain IDs or ephemeral ports [34].

4 Validation

In order to validate the implemented connections between the application and the machines and test them for their robustness, latency tests are carried out. For this purpose, we examine the different components of the communication setup.

4.1 ROS-Unity connection and message flow

With the connection between Unity and ROS2 successfully set up, the rqt_graph looks as below in Figure 5 along when rviz2 is executed. The messages are generated by the Unity AR application and sent to the local computer that is connected to the same network where the ROS server endpoint is running. This received messages are then shared across the VPN tunnel, making them accessible to the computer on board the machine.

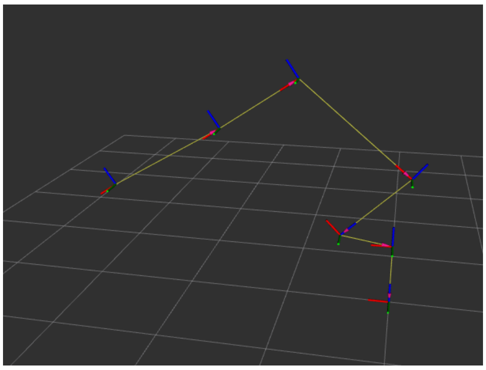

Figure 6. Visualisation of /tf messages of the on-board computer received from the AR application.

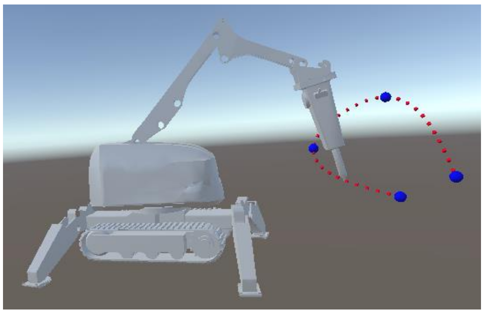

Figure 7. Screenshot of the path planning in Unity.

4.2 Deployed Augmented Reality application

As the connections between the application and the servers are set up, along with the successful built and deployed AR application. The application is run with an image as a target to allow the model to anchor into the digital environment. In Figure 8, the blue points are the waypoints that are used to define the pathway. The red dots show the generated pathway, for which the end effector will follow.

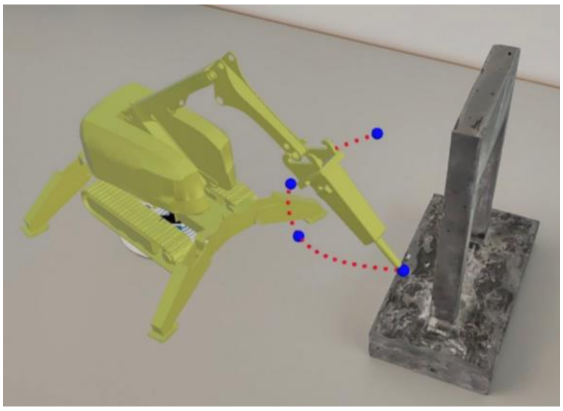

Figure 8. Screenshot of the application using image target as anchoring.

However, as the application is running, some jittering of the model occurred. This causes unwanted transformation, /tf messages of the model to be published. This phenomenon is observed to occur when the user moved the device too fast or when the lighting of the physical environment is insufficient. The jittering also occurred for the object target recognition, it is especially pronounced when the sunlight is too strong, where the reflective surface of the physical BROKK machine to cause glares to the camera.

4.3 Latency result

In order to evaluate the robustness of the 5G network in the construction site, a latency test is carried out with the set up as above. The latency is tested using My Traceroute (MTR) [35] using 100 packages of 64 bytes with a frequency of 10 Hz. The tests are done with varying publishing frequencies from the Unity

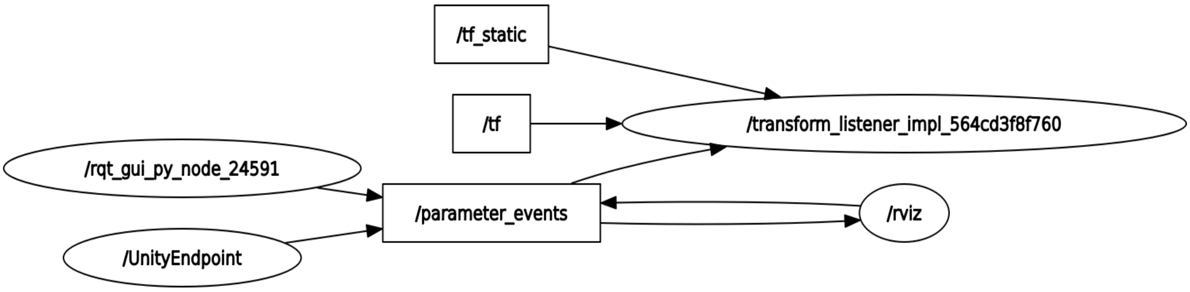

Figure 5. rqt_graph of the connections

application using ICMP, TCP and UDP. The results are tabulated according to the respective protocols.

For all tested protocols, the results for the average latencies are compatible within their respected standard deviation. However, the distribution for the UDP and TCP protocol are noticeably broader when the ROS messages are sent at the frequency of 10 Hz. This is reflected by the comparably larger standard deviations.

Furthermore, it should be noted that the UDP protocol has a package loss of approximately 20%. The best average latency is observed at the publishing frequency of 50 Hz by the ICMP test. And the worst average latency is observed to be at 10 Hz by the UDP test

Table 1: ICMP test

ROS Freq. [Herz]	Loss %	Avg [ms]	Best [ms]	Worst [ms]	StDev
10	0	28.84	20.60	72.55	6.09
50	0	27.58	18.95	39.42	4.24
100	0	28.85	19.34	51.16	6.60

Table 2: UDP test

ROS Freq. [Herz]	Loss %	Avg [ms]	Best [ms]	Worst [ms]	StDev
10	21	34.48	21.61	120.34	19.92
50	19	29.90	21.11	37.36	3.62
100	21	31.37	19.78	49.94	6.06

Table 3: TCP test

ROS Freq. [Herz]	Loss %	Avg [ms]	Best [ms]	Worst [ms]	StDev
10	0	32.71	22.89	130.61	18.94
50	0	28.03	20.06	41.04	3.98
100	0	29.04	18.43	41.04	5.85

5 Discussion

This study shows the entire framework and workflow of developing an AR application with Unity and ROS2, connected via 5G campus network. Unity is chosen not only because of its ability to build a mixed reality application, but also because of its versatile ability to be used with other communication protocols such as MQTT, to develop an interactive user interface, to process and visualise data acquired from various sensors. Although the workflow and implementation of this application is rather complicated and it requires multiple components to realise this particular use case, the application's framework is versatile and can be adapted across a wide range of scenarios with minimum amendments.

In order to realise a multi-network communication between different machines, a P2P VPN is set up so that the machines can discover and communicate with each other. This can however also be achieved by using port forwarding but is advised against due to its potential security risk for it exposes the ports to the public. This is especially undesirable when considering the messages sent are used to control heavy duty robots and any mishaps or hijacking of the port could lead to unthinkable consequences. Using a VPN can highly reduce the risk, albeit causing an increase in latency. One of the reasons for the increased latency is due to the encryption of the packages during transmission. The packages are encrypted with a key and a nonce. This ensures that the packages are kept confidential and with an authentication tag, making sure that the messages are not tampered with.

In the latency test, there is some package loss in the UDP protocol. This is due to the nature of UDP where it does not check for errors nor receipt during transmission, causing some package to be lost during transmission. Looking at the average time of the tests, the messages have a latency of less than 50ms.

6 Conclusions and outlook

This paper shows the successful framework implementation of an augmented reality application enabled through a 5G network. However, the latency and the occasional unstable jitter might need to be improved with accordance to the recommended values as stated in [36]. With regards to the research questions, an AR application has been developed to aid in visualisation and planning of the robotics deconstruction planning. Additionally, the low latency requirement has been leveraged using the 5G network's capability. It is worth pointing out, that this framework of Unity and ROS2 is not limited to as such. The ability to define the domain ID opens the possibility to deploy multiple applications with only one machine to host and act as the control. This framework could also be extended to an AGV or other machines controlled via ROS. Furthermore, safety zones could be defined and visualised such that the machines could communicate with each other, slowing down or stopping immediately with accordance to the position, process and speed of the operating machines. Moreover, the framework allows sensors information e.g., from LiDAR scanners or RGBD cameras to be integrated with computer vision algorithms. This enables the machines to understand the environment and provide an action trigger to whenever something is detected within the vicinity of the danger zones. With the improving bandwidth and decreased latency of 5G network, the proposed extensions of the framework are promising. Subject to future research are cases where there is an ontology server set up within the construction project. Then these actions or triggers detected by the sensors can be forwarded to the ontology. This process imparts semantic meaning to the identified actions and triggers, which in turn fosters effective information dissemination among relevant stakeholders and prompting subsequent actions as needed.

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