Intuitive HRI Approach with Reliable and Resilient Wireless Communication for Rescue Robots and First Responders

Raimund Edlinger[1], Michael Anschober[1], Roman Froschauer[1] and Andreas Nüchter[2]

***Abstract*— In this paper, we present a user-selectable control unit to make complex robot systems easier to operate. Search and rescue robots are primarily used for obtaining information and manipulating dangerous objects or supporting emergency forces in dealing with crisis situations. Based on hazardous mission scenarios in which mobile robot systems are confronted with complex manipulation and manoeuvring tasks (e.g., leakage of contaminants), new methods and concepts in the area of robot decision making, sensor data presentation and control concepts were developed to facilitate the handling and operation of assistance robots. The flexibility of the control concept approach is intended to increase the confidence of the emergency services and to provide intuitive operation of the assistance robots for every user. An intuitive control and stable communication for both control commands and feedback from the robot itself increase trust in the robotic system and its acceptance by the operators. These developments have been investigated in field trials with different types of robots and with network communication constraints.**

I. INTRODUCTION

Fully autonomous systems are currently less applicable to hazardous operations, because in terms of acceptance by first responders. The paper therefore focuses on the importance of an intuitive control interface and for semi-autonomous functions for robotic systems, where the degree of autonomy can be adapted in the interaction between operator and robot. In this context, the operator's trust in the robot assistance system is crucial. Furthermore, the cognitive load, the intuitive operation and the the sensor feedback from the robot through the use of the system is also crucial for its acceptance by the operators. An overview of developments in exciting and challenging area of robotic control and lessons learned for urban search and rescue (USAR) are provided in [1] and [2].

Khasawneh et al. investigates in [3] the relationship between the performance of the human operator of a teleoperated robot and latency at different levels and hypotheses. The need for intuitive and efficient Human-Robot Interfaces (HRIs) from Blueprint Lab[1], wearable technologies and hand-worn haptic interface [4] is still a major research topic. Master slave robot arm controller are realized in [5] or fully automatic visual servoing control in ROV applications [6]. When dealing with crisis situations [7], emergency personnel have specially designed measuring devices, which are usually bulky and hinder the operation. These are worn on the body and thus represent a further burden and contribute to the faster fatigue of the personnel. Another weak point is the communication via radio, due to noise and emerging sounds during an operation, radio messages are often difficult to understand. Valuable seconds are lost due to the subsequent repetition and the operation is massively affected. If an emergency worker gets into a life-threatening situation, faints or is buried, contact with the command center is lost and no information can be obtained. Robot systems can not only reduce this situation, but also ensure in advance whether or not it is responsible to enter the danger zone. Increasing the flow of information and simple control between the robot, mission control and the task force is the main component of the work, making it easier to make decisions relevant to the mission. An essential aspect is to make the robotic system more intelligent. This not only makes it easier to control the system, but also gives the operator the information which is needed to better assess the terrain. The operator can then work out precise plans for the next steps together with the

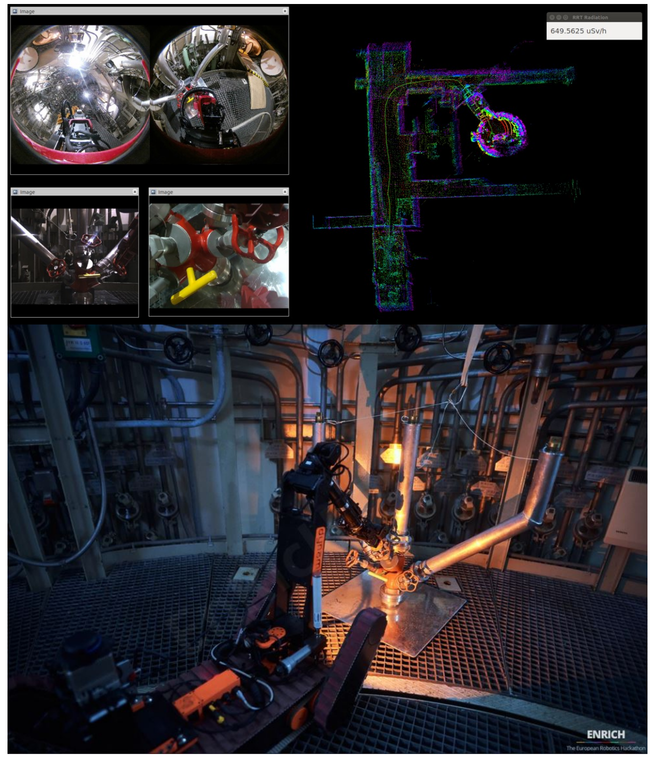

Fig. 1. Human-robot interaction and data visualization in a harsh environment

[1]Raimund Edlinger, Michael Anschober and Roman Froschauer are with University of Applied Sciences Upper Austria, 4600 Wels, Austria raimund.edlinger@fh-wels.at

[2]Andreas Nüchter is with Informatics VII - Robotics and Telematics, Julius-Maximilians University Würzburg andreas.nuechter@uni-wuerzburg.de

[1]https://blueprintlab.com/products/master-arm/

operations management, so that an optimal collaboration between man and machine is created.

II. Related Work

The teleoperation of unmanned vehicles in highly stressed environments is the subject of research in many fields, focusing on the performance of the robot system, the operator and the interaction design. Search and rescue robots serve as a supplement to the emergency forces and provide real-time video, sensor data of the environment and other important information about the situation.

Khasawneh et al. [3] examines the results and analysis between latency and human operator performance of a teleoperated robot. Related research, evaluation and improving the teleoperation with immersive teleoperation systems are done in [8], [9] and [10]. Illing et al. [11] reported a hybrid concept for teleoperation of a mobile robot by using a virtual environment scene with a virtual robot model.

Research in full-body telepresence and autonomous operator assistance mobile robots are presented in [12], [13] or with force-feedback teleoperation [14]. Further a digital twin of the robot offers the representations of the joint states and the 3D model, as well as the dynamic unknown environment [15]. Remotely controlled robotics encompasses a wide range of technologies, particularly unmanned vehicles and robots are operating as UGVs, UAVs, USVs or UUVs. All these technologies are widely used in various domains: A comprehensive crane control is published in [16], haptic controls are essential in telesurgery [17], [18] or telerobotic systems in search and rescue robotics are a special field of teleoperated robotics [19], [13], [20], [21]. The control of mobile rescue robots and manipulators are very often sent via gaming controllers (e.g. wireless Xbox 360, PS4) [22]. Due to the limited number of levers and buttons, the controller mapping must be well considered.

A controller is mainly used in two modes: On the one hand to control the robot base and on the other hand to control the robot manipulator and the position of the gripper. Assigning functions to buttons is a critical task because it must allow the operator to control multiple functions of the robot simultaneously as conveniently and efficiently as possible. In addition to the controller, robot commands are often sent to the robot via the keyboard or other controls via an abstract ROS node that can be easily modified depending on the prioritization of the controller. However, direct control also requires a constantly stable connection to the robot. Reliable and resilient wireless communication for rescue robots and first responders is essential, especially in dangerous situations and when there is no direct view to the robot.

The main contributions of this work are:

- (1) a modular operating unit for quickly activating and deactivating assistance functions and outputting task-specific information with intuitive plug-and-play controls for manipulators
- (2) the evaluation of network communication between operator, robot and sensor system

III. User Interface and Robot System

A reliable HRI depends on several human variables. These variables can be divided in operator performance, perceived workload, and the subjective rating of trust with automation.

A. Modular HRI control

The paper presents a developed control module that can be connected to the control computer both wired and via WiFi. The wireless network is implemented with an ESP32 which is a micro-controller unit with integrated WiFi and Bluetooth connectivity for a wide-range of applications. The efficiency of communication is increased and an easy expansion of the system is enabled. The device is self-powered by its own battery and can be used as a handheld unit by the operator. Another aspect of the design was the arrangement of the levers and various switches. Due to the many mechanisms (e.g. flipper, manipulator) that a mobile robot has and also the assistance functions that can be implemented by software, the operating elements were arranged accordingly. The manipulator module can be adapted to the operator when operating a robot arm. Fig. 2 shows, that the user has the following three choices:

- *Two joystick control:* This option offers the conventional crane control, where one lever can be used for translation (XYZ) and the other lever for rotation (RPY).
- *Master arm controller:* This is a mechanical twin that provides intuitive control and quick operation of the manipulator. The 6-DOF master arm is implemented with 5 Dynamixel motors, where axis 6 can be operated via a joystick for endless rotation, see Fig. 3.
- *3D mouse control:* The SpaceMouse® Module covers both rotation and translation movements due to the 6-axis sensor. The device is available with a USB or serial (UART) interface.

The two joystick control is standard on the control panel, whereas the modular interface allows the user to choose between the 3D mouse and the master arm controller. A

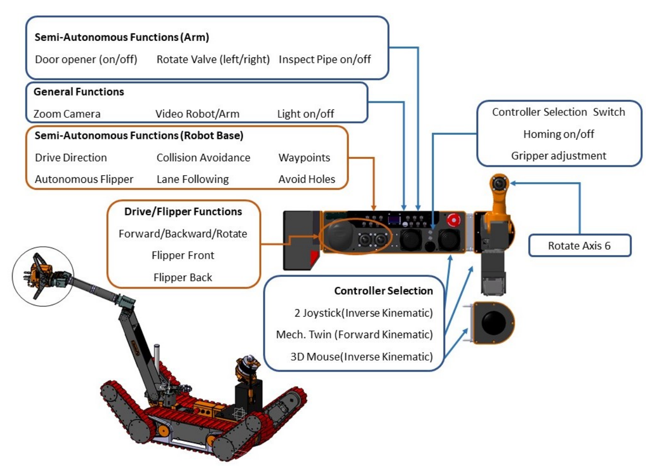

Fig. 2. HRI overview: A tracked rescue robotic system with a 6-DOF manipulator and multi-functional gripping system (left) and a modular User-Interface for controlling the mobile system with a master arm controller/3D mouse controller

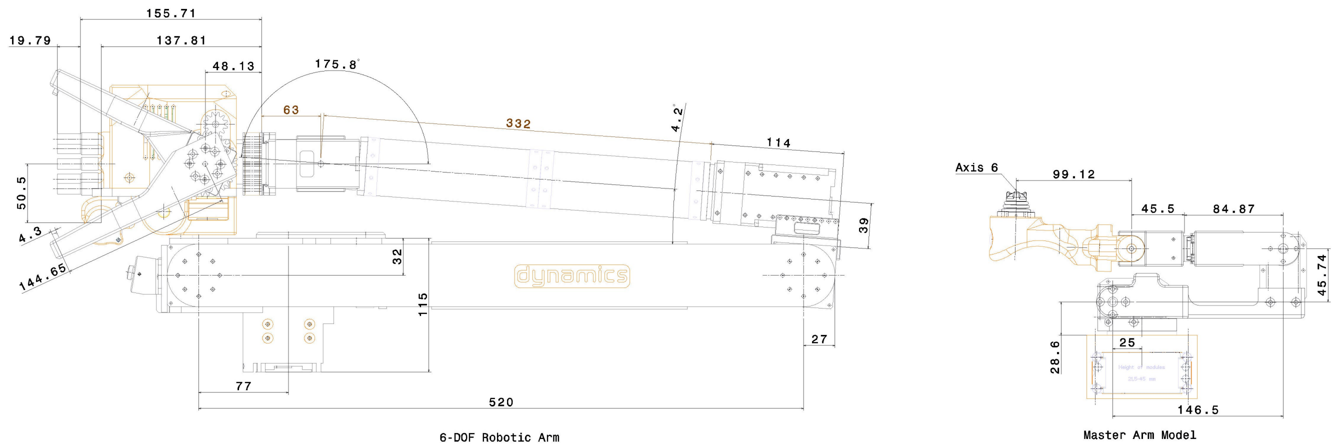

Fig. 3. Configuration, link lengths and coordinates mapping of the small-size 6-DOF robotic manipulator and the corresponding master arm controller.

TABLE I

MOTOR CONFIGURATIONS OF THE 6-DOF MANIPULATOR AND THE MASTER ARM CONTROLLER

Joints	6-DOF Manipulator	Resolution Motor [pulse/rev]	Resolution RRTLAN [pulse/rev]	Master Arm Controller	Resolution Motor [pulse/rev]	Resolution Motor [°]
1	H54-100-S500-R	501,923	65.535	AX-12A	1024	0.29
2	H54-200-S500-R	501,923	65.535	MX-64AT	4096	0.088
3	H54-200-S500-R	501,923	65.535	MX-64AT	4096	0.088
4	H54-100-S500-R	501,923	65.535	AX-12A	1024	0.29
5	H42-20-S300-R	303,751	65.535	AX-12A	1024	0.29
6	H42-20-S300-R	303,751	65.535	1-axis Joystick		

defined interface and connector concept allows easy replacement of the control modules, see Fig. 2. The master arm controller is provided with Dynamixel motors. For joint $1,4,5$ the Dynamixel AX-12A is employed which has a running limitation of $\pm 150°$ in position mode. In contrast to that for joint 2 and 3 the Dynamixel MX64T is chosen which is able to rotate in position control mode between $0° \sim 360°$. An advantage of ROS [23] is that processes (Nodes) communicate with each other by passing standard or self-defined messages. ROS-messages are strictly typed data structure for describing standard data structures and data values. For the Wireless Modular Control Interface (WMCI) the *sensor_msgs/Joy.msg* structure is used, where any input device can be packed into this structure. For the master arm controller, joysticks, buttons and switches a *sensor_msgs/Joy* is publishing the states. For the 3D mouse device *sensor_msgs/Joy* and *geometry_msgs/Twist* are used which outputs the spacenav's six degrees of freedom and its buttons as a joystick message.

B. Visual and Tactile Sensor Feedback

The tracked mobile platform in Fig. 6 consists of two track units connected to a base with four flippers for more off-road mobility. The robot is mainly used for rapid exploration and manipulation for task-related operations. The end-effector of the 6-DOF arm provides multiple functions and high precise handling operations. Eight analogue cameras provide sufficient all-round visibility on the platform for the operator: four cameras provide sufficient all-round vision while driving, and another four can be switched from the control panel and are useful while using the robot arm for various manipulation tasks.

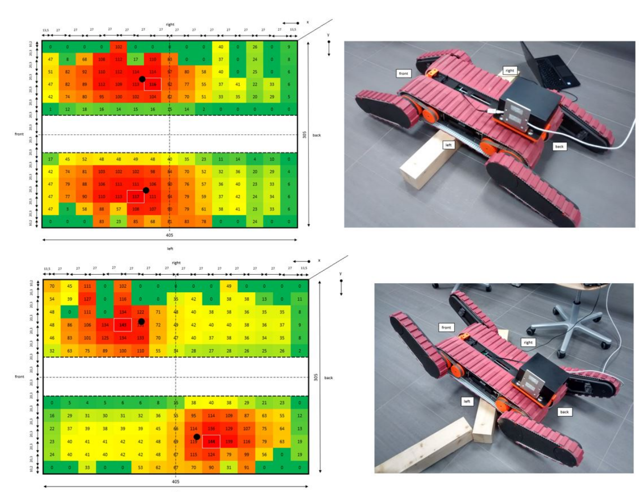

Fig. 4. Sensor feedback and pressure distribution for predictive mobility, safe and stable execution during manipulation tasks

The visualisation of LIDAR and visual data, see Fig. 1, is one of the most important components for the operator, because without this information no robot system can be controlled remotely. To improve the trust to the robotic system a tactile sensor system for tracked vehicles is presented in [24]. The prediction of the resulting track forces knows *a priori*, because it expresses a statement that one can derive by reason alone. The sensor system can be further used as a predictive model for tracked vehicle traversability and to ensure a stable position for manipulation tasks. For the communication between the electronic control system and motor control boards the CAN-Bus interface is used. A ROS-driver for exchange data between the printed circuit borads (PCBs) and a higher level computing unit with the Robot Operating System (ROS) is developed. The used RRTLAN [25] provides almost trouble-free operation of the robot and the ethernet-enabled main controller allows the operator to start the ROS driver at the robot or at the operator station.

C. Kinematic analysis and implementation of an anthropomorphic 6-DOF arm

The 6-DOF manipulator is an essential element for the movement of the Tool Center Point *(TCP)* of a gripper system. A mobile robotic arm, unlike the vehicle platform, is much more difficult to operate and usually requires more practice and experience from the operator. The approach is to minimize the difficulty of operation and simplify complex devices for remote sensing. A further main contribution was to implement the inverse kinematics, which is straight out of a standard robotic, on the micro-controller ATxmega256A3U. Fig. 3 shows the conceptional design and configuration of the 6-DOF arm and the corresponding master arm controller. The figure shows both the size ratio of the robot arm and the control unit, as well as the resolutions of the respective motors. For data exchange, a separate protocol was developed that can communicate with the electronics on the robot and with the controller at the operator station (ROS). The motors of the manipulator have a resolution of 501,923 and 303,751 increments per revolution, respectively. Via the RRTLAN [25] (register mapping) 16 bits are transmitted, i.e. a resolution of 65,535 per revolution. The kinematics of the manipulator is completely described by the Denavit-Hartenberg parameters a_i, α_i, d_i and θ_i of each link i, illustrated in table II. The corresponding transformation matrix ${}^{i-1}\boldsymbol{A}_i$ is used to transform the coordinate system $\{i\}$ into the coordinate system $\{i-1\}$, given as:

$$
\begin{aligned}
{}^{i-1}\boldsymbol{A}_i &= Rot(z_{i-1},\theta_i)\cdot Trans(z_{i-1},d_i)\cdot \\
&\qquad Trans(x_i,a_i)\cdot Rot(x_i,\alpha_i) \\
&= \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cdot\cos\alpha_i & \sin\theta_i\cdot\sin\alpha_i & a_i\cdot\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cdot\cos\alpha_i & -\cos\theta_i\cdot\sin\alpha_i & a_i\cdot\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}
\end{aligned}
\tag{1}
$$

TABLE II

DENAVIT-HARTENBERG-PARAMETERS OF THE FIRST SIX DEGREES OF FREEDOM FROM BASE TO THE TCP OF THE GRIPPER

Link	Joint Variable	θ_i [rad]	d_i [m]	a_i [m]	α_i [rad]	Range
1	φ_1	φ_1	0.083	0.077	$-\frac{\pi}{2}$	±90°
2	φ_2	$\varphi_2-\pi$	0	0.52	π	0°...180°
3	φ_3	$\varphi_3-\frac{\pi}{2}$	0	0.066	$\frac{\pi}{2}$	0°...180°
4	φ_4	φ_4	0.419	0	$-\frac{\pi}{2}$	±180°
5	φ_5	φ_5	0	0	$\frac{\pi}{2}$	±135°
6	φ_6	φ_6	0.255	0	0	endless

1) Forward Kinematics: Forward kinematics is the determination of the position and orientation of the *TCP* in relation to the base depending on the joint variables. The forward transformation, also referred to as direct transformation, results from a chain transformation of the individual transformation matrices stated in equation 2.

$$
{}^{0}\boldsymbol{T}_6 = {}^{0}\boldsymbol{T}_1\cdot{}^{1}\boldsymbol{T}_2\cdot{}^{2}\boldsymbol{T}_3\cdot{}^{3}\boldsymbol{T}_4\cdot{}^{4}\boldsymbol{T}_5\cdot{}^{5}\boldsymbol{T}_6 \tag{2}
$$

The composition of the homogeneous transformation matrix ${}^{i}\boldsymbol{T}_{i+1}$ of dimension $[4\times4]$ is described in equation 3. The vector ${}^{i}\vec{p}_{i+1}$ of dimension $[3\times1]$ (cf. equation 4) represents the translation and the matrix ${}^{i}\boldsymbol{R}_{i+1}$ of dimension $[3\times3]$ (cf. equation 5) represents the rotation of a body in space. Due to the capability of representing both translation and rotation in a homogeneous transformation matrix, matrix calculations can be applied to describe robot kinematics. The pose of the *TCP* in relation to the base coordinate system, consisting of the spatial position and orientation, can thus be expressed by the transformation matrix ${}^{0}\boldsymbol{T}_6$ and provides a unique solution.

$$
{}^{i}\boldsymbol{T}_{i+1} = \left[\begin{array}{c:c} {}^{i}\boldsymbol{R}_{i+1} & {}^{i}\vec{p}_{i+1} \\ \hdashline \vec{0}^{T} & 1 \end{array}\right] \tag{3}
$$

$$
{}^{i}\vec{p}_{i+1} = \begin{bmatrix} {}^{i}p_{i+1,x} \\ {}^{i}p_{i+1,y} \\ {}^{i}p_{i+1,z} \end{bmatrix} \tag{4}
$$

$$
{}^{i}\boldsymbol{R}_{i+1} = \begin{bmatrix} {}^{i}R_{i+1,xx} & {}^{i}R_{i+1,yx} & {}^{i}R_{i+1,zx} \\ {}^{i}R_{i+1,xy} & {}^{i}R_{i+1,yy} & {}^{i}R_{i+1,zy} \\ {}^{i}R_{i+1,xz} & {}^{i}R_{i+1,yz} & {}^{i}R_{i+1,zz} \end{bmatrix} \tag{5}
$$

Hence, the calculation of the individual transformation matrices of each link based on the joint variables and manipulator geometry is required. The transformation matrices can be obtained according to the Denavit-Hartenberg convention (cf. equation 1). It should be noted that the assignment of the coordinate systems according to the Denavit-Hartenberg convention does not necessarily correspond to the desired assignment of the joint coordinate systems. Due to this reason, additional transformations may be necessary to achieve the desired representation. For manipulators with simple

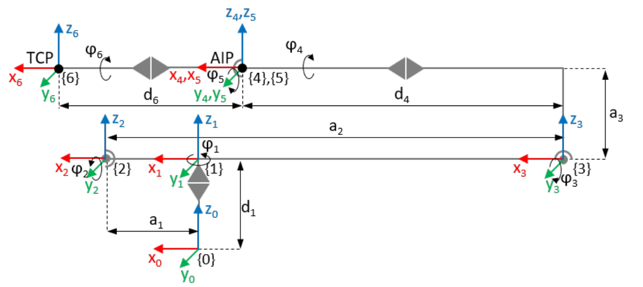

Fig. 5. Schematic sketch of the robot arm with assigned coordinate systems used for forward and inverse kinematics, $\varphi_1 \ldots \varphi_6 = 0\ rad$

geometries, the transformation matrices can alternatively be obtained by translations and elementary rotations in relation to arbitrarily assigned joint coordinate systems. For this robot arm, the forward and inverse kinematics were developed according to the sketch illustrated in Fig. 5.

2) Geometric Solver for Inverse Kinematics: Inverse kinematics or backward transformation describes the inverse operation of forward kinematics, i.e. the determination of the joint variables at a given pose of the *TCP*. In contrast to forward kinematics, inverse kinematics generally does not provide a unique solution. Thus, the robot arm was analyzed to develop an inverse solver in order to resolve the joint angles $(\varphi_1 \ldots \varphi_6)$ based on the pose of the *TCP*. Due to the geometry of the manipulator, there are generally eight different solutions for combinations of joint angles to achieve the desired pose. This results because

1) the base of the manipulator, which is defined by joint $\{1\}$, can be oriented towards or away from the axes intersection point *AIP*,
2) the elbow formed by joints $\{2\}$ and $\{3\}$ can be oriented upwards or downwards and
3) the orientation of the wrist is identical every half turn of joints $\{4\}$ and $\{6\}$ and the corresponding angle of joint $\{5\}$,

hence $2^3 = 8$ solutions.

The operator can choose between 3D mouse and crane control (two joystick control) with inverse kinematics. For the movement of the master arm controller, a button has been integrated on the front of the handle that, when pressed, it sets the stall torque from the motors to zero. As soon as the button is deactivated again, the motors are set to the holding torque. This allows the operator to leave the master arm controller during manipulation tasks and perform other activities. The mechanical twin offers easy operation for everyone, but for very precise manipulation tasks, such as precise execution or pinpointing, this system has disadvantages. The angles from the mechanical twin are mapped $1:1$ to the real manipulator. You can manipulate to a point very quickly, but the precise execution could be improved in the future. Reliable operation of the robotic system is also related to appropriate network architecture and low latency, which will be discussed in more detail in the next chapter.

IV. Network System Concept

The robot and operator control are equipped with a UBIQUITI Networks 802.11a/b/g Bullet M5 Access Point/Bridge that connects wirelessly to the identical access point on the robot platform module. To ensure stability and robustness of communication over long distances, the access points are able to operate between 0.1 mW and 0.5 mW power basis. All connections between the robot's access point and other computing nodes (e.g. Gigabit switch, control board, video encoder, onboard PC) on the mobile platform are established via Ethernet. In addition, we use the TCP/IP communication protocol to transfer control commands between operator control unit and the micro-controller-based boards. The vSTING (Spatially Distributed Traffic and Incident Generation) Module [26] is installed between the teleoperated robot and the operator's computer, see Fig. 6. The module is controlled via a web user interface, further referenced as the vSTING controller, which is accessible on the iPad mounted on the vSTING module. The constraints selected through the vSTING controller are applied on the traffic forwarding ports of the vSTING module via transparent MAC-Layer network emulation. A simplified representation is depicted in Fig. 6 below. In this context, sound and practical control concepts for assistance systems were developed. In order to achieve sufficient validity about the handling and the influence on the confidence and stress from the operator, the developments were supported and verified by experimental investigations with different operators and prior knowledge in realistic application scenarios.

The NIST standard test methods were used as application scenarios, which were designed for the evaluation of different robot and operating units [27]. One application mapped to real-world scenarios is the EnRicH competition [28], which takes place every two years at the Zwentendorf nuclear power plant. Here, the robot teams have the opportunity to explore the nuclear power plant and search for radioactive sources during a hackathon lasting several days. The duration of the mission is limited to 45 minutes, which means for the operator that the mobile robots have to operate as quickly and reliably as possible and find as many sources as possible under time pressure.

V. Use-Case Evaluations

The HRI approach has shown during the participation in the RoboCup German Open at the DRZ Research Center in Dortmund and at the EnRicH at the Zwentdendorf nuclear power plant that the execution of complex operations (e.g. manipulation of doors, valves, or exploration of difficult terrain) can positively evaluate the overall system.

A. Manipulation with the Mechanical Twin

Remote control of a robot requires good knowledge of the robot itself, as well as responsiveness and response. It was found that inspection tasks are performed very quickly and easily with the mechanical twin. Manipulation tasks include gripping or manipulating objects (e.g. valve turning). Fig. 7 shows closing the corresponding valve, after identifying

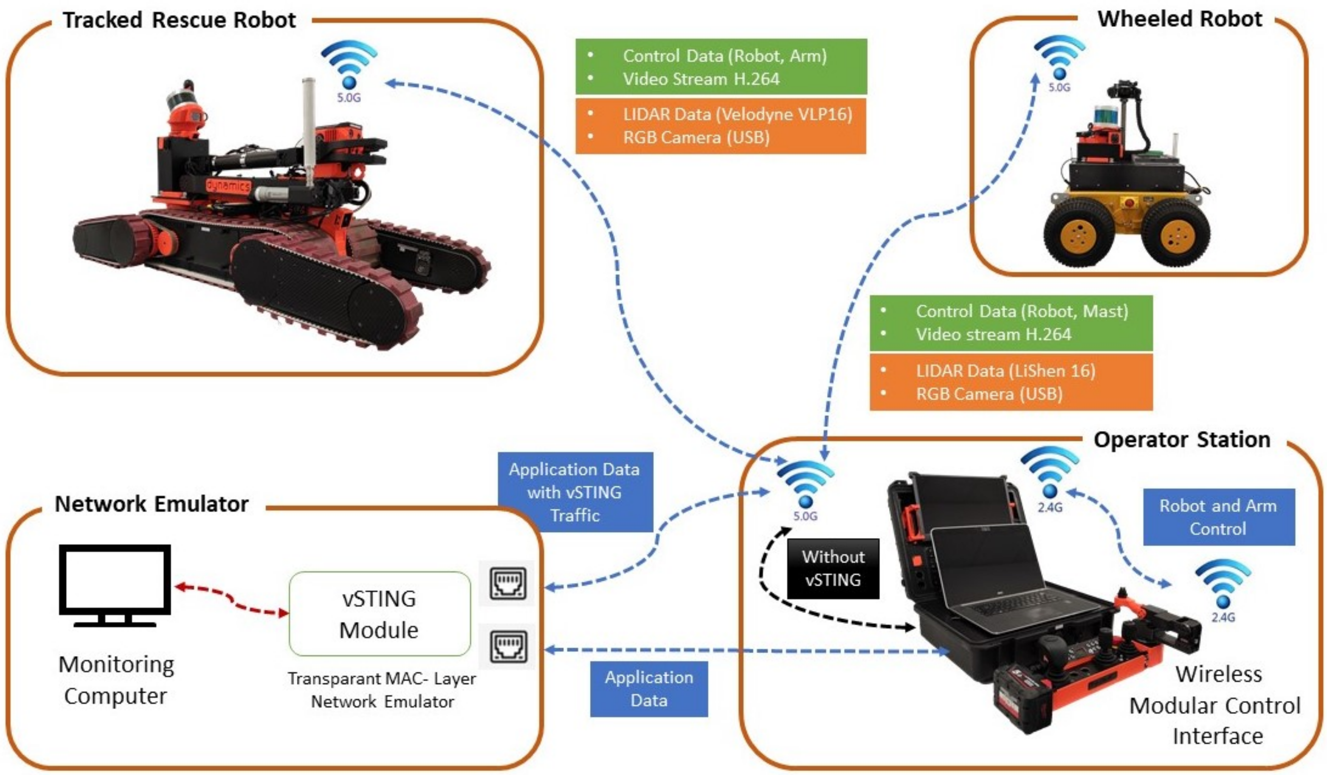

Fig. 6. Cross-domain application of the STING (Spatially Distributed Traffic and Incident Generation) concept from TU Dortmund [26] for testing the resilience of mission-critical human-robot communications.

a specific pipe containing radioactive coolant. Closing the valve seems easy at first glance, but for the operator it is important how the robot stands in relation to the manipulating object and how many degrees of freedom and what working range the robot arm has. The precise execution of the robot arm by the mechanical twin cannot be implemented perfectly, because every movement of the mechanical twin is executed by the operator 1:1 to the real arm. The experiments have also shown that linear movements are difficult to implement through the model, unless a linear axis is built into the system. This extension would bring some advantages in the last section in the manipulation process and would allow a punctual execution.

B. Network Performance

The setup of the network performance test at the German Rescue Robotic Center in Dortmund during the RoboCup German Open - DRZ edition consists of four traffic cones placed in a row with a distance of 1 m between the centers of each cone. On the floor there are markers for the start position and for the respective traffic cones, in order to visually evaluate at the end how many rounds the robot will drive and on which position it will finally stand. For the network setup and evaluation at the DRZ a *vSTING* Module [26] was installed, which was provided by TU Dortmund between the teleoperated robot and the operator's computer, see Fig. 6. To effectively record the sensor data received from the robot and the control commands received from the operator, at least two recording processes must be started: one on the robot to record the control commands coming from the operator, and one on the operator's computer to record the robot's sensor data. The evaluation will be conducted in five runs. Each evaluation run will evaluate the performance with a different emulated communication setting. The operator has no view of the robot and must rely purely on visual images and the controller. Each run is lasting a fixed time of 3 minutes after which the evaluation is stopped and the metrics and recordings are gathered.

In the following the five different settings for the five runs

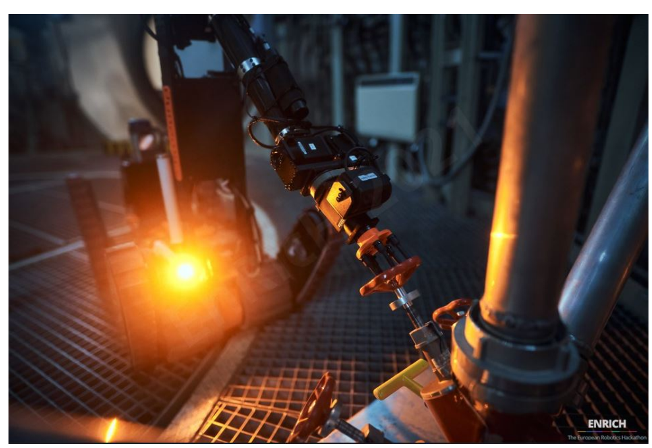

Fig. 7. Valve closing at EnRicH in NPP Zwentendorf

are defined:

- 1.) Reference Run: There are no added communication constraints, although vSTING is already in the Loop.
- 2.) Rate Limit Run: The system introduces a fixed rate limit of 10 Mbit/s (Bucket filter) on the communication link.
- 3.) Packet Loss Run: The system introduces a fixed randomized packet loss of 10% on the communication link, see Fig. 9.
- 4.) Latency Run: The system introduces a fixed additive latency of 100 ms on the communication link, see Fig. 8.
- 5.) Full Constraints Run: The system introduces the following constraints: - an additional latency of 100 ms - a packet loss of 10% - and a fixed rate limit of 10 Mbit/s (Bucket filter) on the communication link.

Fig. 10 and Fig. 11 illustrates the incoming and outcoming traffic on the robot and the operator side. The overlap of the data in Fig. 10 and Fig. 11 shows that the commands are sent in near real time from the control unit to the robot system. The data exchange (commands and video stream) between robot and operator took place almost in real time during the network performance test at the DRZ. The robot sent commands for controlling the robot, flipper system and robot arm as well as collected telemetry data (e.g. temperature, battery status, motor currents, etc.) over the wireless network. When driving, the operator has up to four video streams that are dramatically reduced in bandwidth by a video encoder with an H.264/H.265 video compression. The video encoder supports HD analog and standard resolution analog cameras with support for two-way audio communication. The limitation of the data to 10 Mbit/s also had no influence on the respective runs, because no more than 8.5 Mbit/s are used for the control commands, telemetry data and video transmission. HD video and LIDAR data were not included in the transmission. These data were further processed on-board on the robot for AI and mapping algorithms.

VI. DISCUSSION AND FUTURE WORK

The direct coupling of robot operation, sensor feedback and environmental perception allow a lot of freedom in the interaction design. An intuitive HRI can significantly increase cognitive load and trust in the assistive robot. In addition, improved assistance systems should facilitate the operation of complex robotic systems and thus also enable access for inexperienced operators. The experiments have shown that the mechanical twin is very easy to handle for the operator and that no highly qualified personnel can control complex robots and manipulators. The operation of the mechanical twin also showed that a quick movement of the arm to the object is possible, but a precise execution with this system is only possible with considerably more time and practice. Due to the coupling of all joints, a linear execution, for example, is very difficult to implement. For this reason, the operator should be able to change the mode. The implementation of inverse kinematics in RRTLAN also shows the necessity. The modular control concept for robot and manipulator has shown that the flexibility and control selection offers advantages for the operator. The confidence in an intuitive control and also the stable communication to the robot system thus also increase the acceptance of the

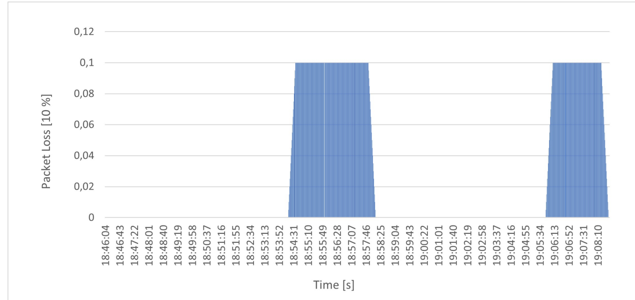

Fig. 9. Packet Loss Run (Run 3 and 5)

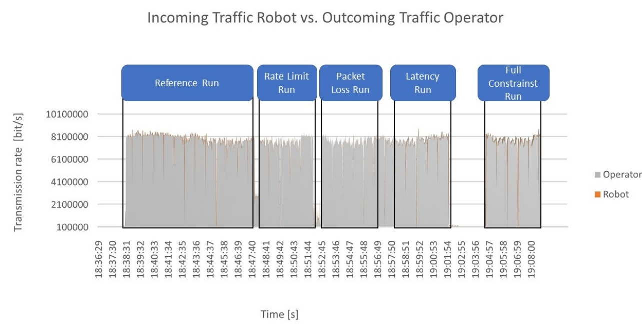

Fig. 10. Incoming Traffic Robot vs. Outcoming Traffic Operator

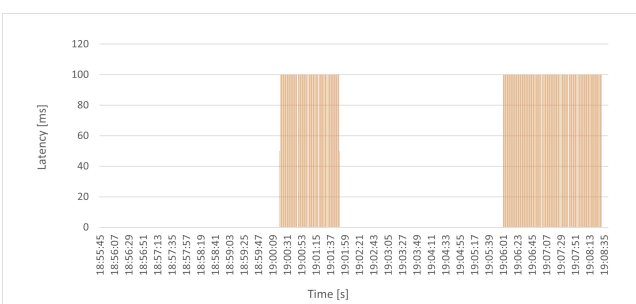

Fig. 8. Latency Run (Run 4 and 5)

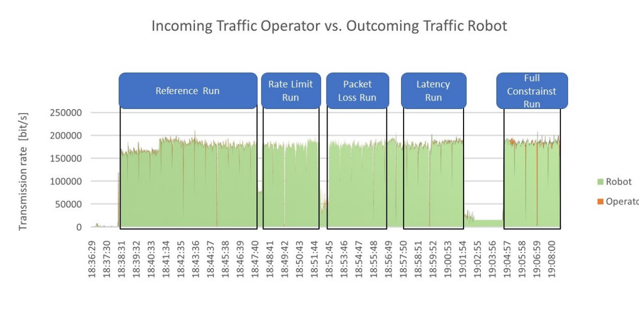

Fig. 11. Incoming Traffic Operator vs. Outcoming Traffic Robot

operators.

In the future, we will still look at the precision of the design and control for the robot arm and make further improvements. Furthermore, we will use the forces and moments from the real manipulator as force feedback for the mechanical twin to give the operator even more feedback from the robot. The HRI Approach has been tested in various field tests before. A standardized evaluation of ethical and psychological aspects regarding the intuitive operation and acceptance of assistive systems is planned in the future with the corresponding users. Network performance testing in the DRZ showed that the entire robotic system performed excellently in every setup. With a mission time of 3 minutes per test, we were able to complete between 12-13 rounds on each test. Even the network restrictions on the entire system could not affect the operation of the robot. The overall control system as well as the video transmission gave the operators the feeling and confidence that they could rely on the control commands. In the future, the existing network will be configured as a mesh network, so that the system can still be controlled over longer distances or inside buildings with thick walls (see nuclear power plant in Fig. 1) and communication with the robot is maintained.

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