

Investigating the Impact of Communication Delays and Bandwidth Restrictions on Remote Operations of Unmanned Systems

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Summary: While autonomy of unmanned systems is advancing rapidly, human oversight remains essential due to legal and operational constraints, making communication a critical factor. This paper explores the impact of communication delays and bandwidth limitations on the remote operation of those systems, focusing on long-range offshore underwater missions conducted with extra-large unmanned underwater vehicles as mobile operation platforms. In such scenarios, communication impairments, such as delays, jitter, bandwidth restrictions, and packet loss, can severely affect human remote control of the system. We address this challenge in the context of uncrewed underwater vehicles, which often rely on multi-hop communication via buoys to extend the range of remote control, and propose a methodology to empirically investigate the communication impact. Through preliminary experiments with remotely operated vehicles, we collect real-world data for further analysis and simulation.

Keywords: Unmanned system (UxV), XLUUV, Remote control, Communication, Link quality, Field trials, Simulation.

1. Introduction

The rapid evolution of unmanned systems (UxVs) in various domains, including aerial, terrestrial, maritime, and underwater environments, has significantly expanded their potential applications [1]. These systems offer promising solutions for tasks such as exploration, surveillance, as well as inspection, maintenance, and repair (IMR) [2, 3]. While the trend is towards increasing autonomy, precise in-situ operations but also regulatory and safety considerations still require human actions and oversight, keeping operators *in the loop* and necessitating continuous communication between the operator and the system. Thus, this reliance on communication remains a key challenge, especially in dynamic environments, where bandwidth limitations, communication delays, and disruptions in connectivity can severely impact the performance and reliability of remote-controlled operations.

As unmanned systems venture farther from their operators, they often exceed direct communication ranges, necessitating networked, multi-hop communication infrastructures to bridge these gaps. However, additional network latency, jitter, bandwidth restrictions, and even bit errors can degrade the quality and responsiveness of the control link, ultimately affecting the system's ability to perform its tasks [4]. While waypoint-based navigation and general piloting tasks can usually tolerate a lot of communication impairment, more precise operations such as the fine-tuned real-time control required for UxV-based IMR missions may much more sensitive to these issues.

Previous research on the impact of communication constraints has primarily focused on the quality of experience (QoE) for video transmission, particularly in the context of improving video codecs for better streaming performance, e.g., [5, 6]. However, less attention has been paid to the impact on remote control systems that require continuous visual feedback for effective operation.

This paper proposes a methodology to investigate how communication constraints affect the ability to remotely control unmanned systems, with a particular focus on operations requiring real-time feedback loops. Although this study specifically focusses on underwater UxVs, particularly extra-large unmanned underwater vehicles (XLUUVs), operating as motherships with communication buoys to extend radio-based communication over greater distances, the findings are applicable to other domains as well.

In this paper, we introduce our work-in-progress. In Section 2, we provide background information on our scenario and the tools we rely on and briefly discuss the related work. Then, our methodology together with preliminary experimental results from field trials conducted in a shipbuilding test facility is presented in Section 3, where we assessed the impact of communication impairments on the operation of remotely operated vehicles (ROVs). These experiments provided valuable real-world data, which was later used to develop simulations for further analysis, as described in Section 4. Finally, Section 5 concludes the paper and derives implications for future remote-control systems and communications infrastructure.

2. Background

2.1. XLUUV and Reference Scenario

Not just since the recent escalation of sabotage attacks against critical maritime infrastructures such as pipelines and submarine cables in the Baltic Sea, there has been a massive demand for underwater surveillance and IMR operations. Unmanned systems offer enormous added value and enable new possibilities [2, 7].

The new XLUUV class represents a ground-breaking trend in this context [8]. These vehicles are the largest UxVs in existence and are designed for long-term missions with ranges of over thousands of kilometers. They often serve as a carrier platform for transporting underwater equipment or special exploration or maintenance payloads such as ROVs.

The large modular Modifiable Underwater Mothership (MUM) [9], depicted in Fig. 1, is one of the vehicles currently developed in the XLUUV class. Particularly due to its extreme modularity, it is used in this paper as an example of versatile UxV. In contrast to the air, land, and (surface) maritime domains, the underwater domain is also exceptionally challenging, as underwater communication is only possible to a very limited extent. The reason for this is of a technical nature: electromagnetic waves, which are used in traditional terrestrial radio communication, are too strongly attenuated by the medium of water. Therefore, acoustic communication must be used, with the disadvantage of significantly lower bandwidths and, above all, signal propagation speeds.

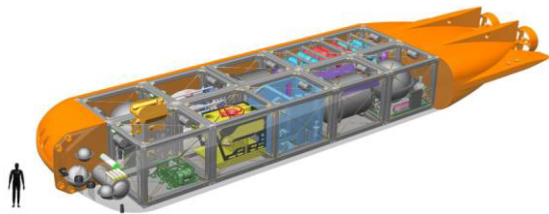


Fig. 1. The modular XLUUV concept of the Modifiable Underwater Mothership (MUM) with interchangeable, container-sized modules and a total length of 25 m in its planned demonstrator, cf. [10].

For remote control by an operator, radio communication with the shore side is therefore usually established at the operation site. This is done either by surfacing the vehicle or (as is also possible with MUM) by deploying a communication buoy connected by cable. MUM has a multi-link communication system that allows users to choose between technologies such as HF radio, Wi-Fi, but also Public Land Mobile Network (PLMN) or satellite communication (SatCom) technologies, depending on their availability [3], cf. Section 2.2. At operating sites far from the coast, there is usually no alternative to SatCom. One possible scenario for MUM's remote control, which will serve as a reference in this paper, is ROV work

tasks, as shown schematically in Fig. 2. Just as the general dependence of the control of XLUUVs on a stable communication link is obviously already part of HAZIDs [10], there must also be a potentially very fine degradation in the control capability for applications with high precision requirements in the future, to which our work makes an initial contribution.

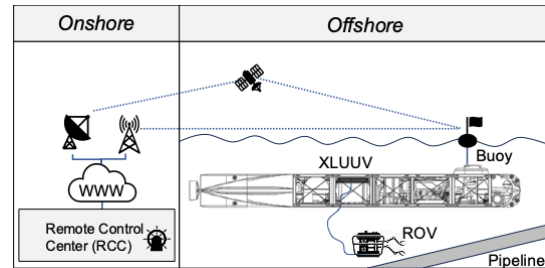


Fig. 2. Schematic representation of the reference scenario of this paper: An operator in an onshore control center remotely steers the UxV, i.e., the ROV of an XLUUV, using one of the available communication links to inspect, maintain, or repair a pipeline.

2.2. Communication Impact in Related Domains

The impact of communication delays and bandwidth limitations has already been studied in various fields for applications involving geographically distributed systems. One notable example is in the domain of distributed music concerts, where synchronization of audio and video across multiple locations is crucial for a seamless experience and network delays and jitter can disrupt synchronization, negatively affecting audience perception [11, 12]. Medical teleoperations, particularly in remote surgery with devices that offer haptic feedback, are another example where communication reliability is even more critical. Delays and bandwidth constraints can significantly compromise the precision and safety of procedures, but a poor video quality alone can also lead to dangerous operator fatigue [4]. Approaches to mitigate these issues often focus on improving network protocols and employing error correction techniques to minimize packet loss and ensure consistency. Moreover, there is a strong focus on developing low-latency communication technologies, such as 5G, to meet the high demands of remote medical applications [13].

Both areas underscore the importance of robust communication systems in time-sensitive, high-stakes operations. In contrast to the long-range application of typical UxVs, however, broadband cable connections, e.g., fiber optics, and sometimes specially leased lines are usually used in these areas, apart from the efforts with 5G technology. The networked locations are stationary, whereas UxVs are mobile and require wireless communication, even in areas where no corresponding infrastructure is available, such as in the maritime domain. Hence, other, UxV-specific technical solutions are necessary for optimum communication here.

2.3. Communication Technologies and Protocols

As reliable data transmission is essential for real-time control, communication plays a pivotal role in the operation of UxVs. Different and partly complementary wireless technologies are available for this purpose, as already mentioned in the previous section.

While smaller drones, for instance, typically use proprietary radio frequency signals or Wi-Fi, more advanced systems use emerging PLMN and SatCom technologies to operate over long distances such as 5G [13] or Low Earth Orbit (LEO) satellite constellations like the popular Starlink [14]. Compared to their predecessors, these promise higher data rates and lower latency times. In maritime applications, offshore without an existing communications infrastructure, LEO SatComs are ultimately the only choice. In addition, federations or swarms of (semi-)autonomous UxVs are increasingly using mesh networks and ad-hoc communication systems to maintain a stable connection in dynamic and remote environments.

As different as these technologies are, so different are their characteristics in terms of delay, jitter, throughput, and bit error rates and packet loss, respectively. Protocols that build on the Internet Protocol (IP) stack they provide address these properties in different ways depending on the application purpose and specialization.

One of these protocols, which is widely used in the context of UxV control, is MAVLink [15, 16], a lightweight, open-source protocol primarily used for data transmission between UxVs, internal components, and remote control centers (RCCs). Using the IP/UDP stack, the transmission is facilitated by serializing system states (e.g., sensor/actuator values, commands, etc.) into compact messages at the application layer. This flexibility ensures that the protocol is not limited to Ethernet or Wi-Fi and allows users to configure these layers based on the system's specific requirements.

Each MAVLink message consists of a compact header containing meta-information, along with a user-defined payload. The protocol's library handles the binary serialization and deserialization of messages, minimizing overhead compared to formats like XML or JSON. By omitting message structure and encoding content in binary, the message's content is identified by a message ID (MSG ID).

Due to its lightweight nature, MAVLink does not incorporate advanced security features. Basic connection integrity is provided by a simple checksum and an increasing sequence number (SEQ). In version 2, an additional cryptographic signature for message authenticity is optionally available.

2.4. Link Emulation with *Link 'em*

With *Link 'em* Schütz et al. [17, 18] introduce an open-source link emulation approach that is based on the popular network emulator *netem*. The tool is

implemented as a common layer-2 bridge and builds on Python's *NetfilterQueue* and the mathematical framework *SageMath* to enable more realistic packet loss models that can be used in addition to the existing ones.

The main contributions of *Link 'em* are two reproducibility-oriented extensions that overcome the shortcomings of *netem*'s random number generation which does neither support a seed nor has a trace-based emulation feature [17]. With those extensions, it is now possible i) to initialize the existing packet loss models, e.g., the widespread Gilbert-Elliott model, with a parametrizable, fixed seed, enabling a deterministic and reproducible model behavior and ii) to emulate packet loss, jitter, message corruption and duplication based on prerecorded network trace files (in Pcap format).

The prototypic implementation of *Link 'em* uses a Raspberry Pi 3 system on a chip (SoC) as the underlying hardware platform. Since this device does not have two network interfaces required to provide a layer-2 bridge, a USB Ethernet dongle (Realtek 8153) was connected to the SoC. However, this USB workaround limits the overall throughput of this implementation and thus also the potential of the approach.

3. Experiments

3.1 Goal and Setup

The main objectives of the project partners in the field trials, which were carried out at a maritime test facility (VWS) of the Berlin Institute of Technology, Germany, were to perform functional tests of the navigation sensors, measure drag values of towed vehicles and test their actuator allocations, i.e., driving, buoyancy, and trim control. At the same time, we were able to take advantage of the field trials with ROV experts to investigate the control capability of the vehicles for a human operator under suboptimal or difficult communication conditions that can occur with different radio technologies.

The basis for our experiments is the network tool *Link 'em* (see Section 2.2), which we have adapted for the ARM SoC NanoPi R4S. This offers two Gigabit Ethernet interfaces on its board and is therefore perfectly suited to be integrated into the ROV control system as a man-in-the-middle for our purposes.

The concept of our setup is shown in Fig. 3. The communication link between the operator terminal and the ROV is interrupted in the Ethernet cable by the NanoPi, whereby all data traffic is recorded for later analysis and the link quality is modified step by step by parameterizing it with *Link 'em*.

3.2 Preliminary Results

The actual implementation of the setup concept can be seen in Fig. 4, together with a BlueROV2, which

was controlled in the test series. While the experienced operator steered the ROV and moved it precisely around a target underwater, the link qualities were successively degraded and the response of the operator, who compensates for a certain degree of interference with his trained skills, was monitored on the one hand, and the ROV movements were observed on the other.

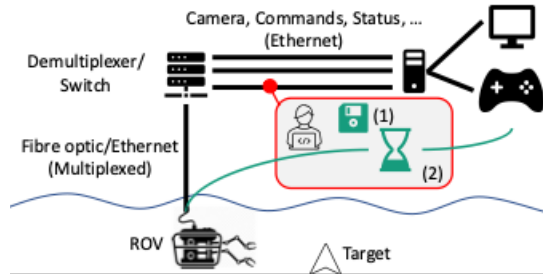


Fig. 3. Setup concept of the real-world experiments. The communication link between the operation terminal and the ROV is controlled by a *Link 'em* device that intercepts and stores all data traffic (1) and artificially modifies the link quality (2), which can affect physical interactions of the operator with an underwater target.

The preliminary and subjectively perceived results of the experiments can be summarized as follows.

With an artificial delay of up to around 100 ms, the vehicle remains controllable. From 200 ms, the sonar image was severely impaired and was finally completely unusable from a transmission delay of 400 ms. From 500 ms, interference was clearly noticeable in the video stream, even apart from the sonar image, but rough control was still feasible, although precision work was no longer possible. A delay of >1 s resulted in massive lags in the video stream and the vehicle was only very marginally controllable. Missions cannot be carried out under any circumstances. In contrast, it was found that jitter has only a minor effect and is hardly noticeable if it is within normal limits.

In terms of bandwidth, we were able to determine a demand of approx. 15 mbit/s for the ROV control. If the link was restricted more, the video breaks down, whereas control commands still could be exchanged. However, remote control without video was no longer possible.

Finally, it should be emphasized that this experiment was mainly a first impression of the challenges that can arise for an operator due to suboptimal communication. Further experiments with other experts are necessary for well-founded statements. Nonetheless, initial experiences, but also network traces and video material could be collected, which were used for a simulation environment.

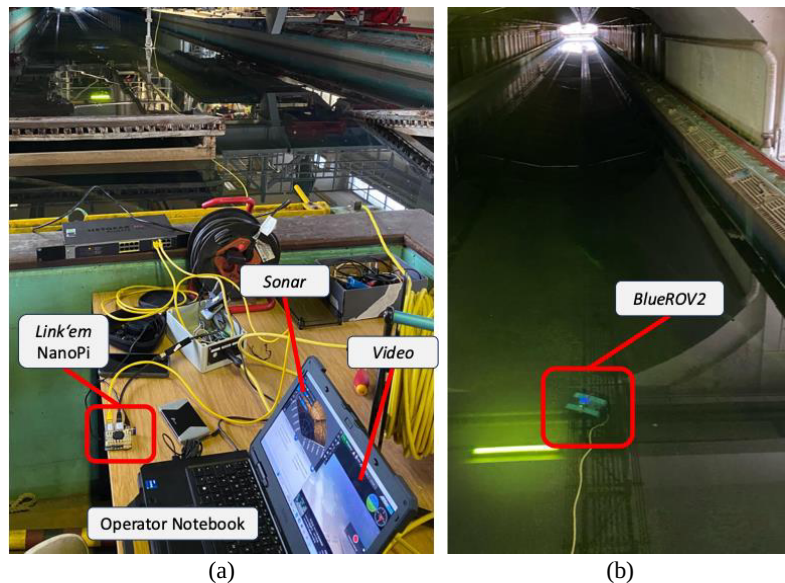


Fig. 4. Conducting the experiment. The setup (a) implemented in the test facility, consisting of the operator notebook, which can be used to control the ROV with a controller. In addition to status information, the sonar image and an optical video image are displayed on the notebook. The communication cable between the notebook and the ROV was interrupted for the experiment by a small system on the chip (SoC) computer (i.e., a NanoPi) with the modified *Link 'em*. This device can now be used to restrict the link quality of the control communication as required, which affects the control capability of the ROV in the towing channel (b) to varying degrees.

4. Transferring the Experiment to Simulation

Real tests such as the experiment described in the previous section are not only time-consuming but also require access to suitable test environments and

equipment. Even if such experiments offer a high degree of realistic accuracy and are essential for well-founded conclusions, it is also essential to switch to low-cost and widely available simulations in pre-development phase for the evaluation and

open-source link emulation bridge and enables the system to simulate various network conditions, facilitating more accurate performance evaluations. Potential applications for the proposed framework can be seen in research, development, and testing of underwater robotics, remote-controlled systems, autonomous devices with human-in-the-loop schemes and other fields where reliable communication is crucial.

Future work will focus on the application of the presented framework to evaluate critical thresholds for the various parts of the system to still provide an acceptable user experience, focusing on autonomous systems under human supervision or remote-controlled devices in remote conditions or challenging communication setups that require interaction to properly deliver results. One potential goal is to deliver threshold values to stakeholders that enable them to decide whether or not a system can be used under certain circumstances or allow the system to self-diagnose its connection and evaluate if and how it can still depend on human guidance. Systems could start recovery procedures when required or automatically switch to emergency operations when, despite a principally working connection, reliability of human control might be declining. Ultimately, this would allow the system, based on potential training data, to calculate the current QoE for a given type of user and the environment and, thus, to e.g., calculate routes or mission plans based also on the notion of the expected user interaction. Another topic is the synthesis of system communication: With the given system virtualizing the various aspects of the given UxV communication, entire communication chains, and protocols can be generated based on simulated or virtual environments, allowing this suite to serve as a foundation to not only test the system but also to check if high-level requirements concerning the communication in adverse environments hold without requiring in-situ campaigns, potentially reducing the cost for the tests significantly.

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