

A hybrid acoustic-RF communication framework for networked control of autonomous underwater vehicles: design and cosimulation

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Received: 06.09.2021

Accepted/Published Online: 04.01.2022

Final Version: ..2022

Abstract: Underwater control applications, especially ones using autonomous underwater vehicles (AUVs) have become very popular for industrial and military underwater exploration missions. This has led to the requirement of establishing a high data rate communication link between base stations and AUVs, while underwater systems mostly rely on acoustic communications. However, limited data rate and considerable propagation delay are the major challenges for employing acoustic communication in missions requiring high control gains. In this paper, we propose a hybrid acoustic and RF communication framework for establishing a networked control system, in which, for long distance communication and control the acoustic link is used, and in the short range, the RF link is employed. Our scenario for testing implements a docking maneuver application, where a docking station determines the positions of the AUVs via acoustic or RF communication, and different medium access schemes are used for coordinating the transmission of the nodes according to the communication mode. Considering the full dynamics of the entire system for controlling the AUVs, the real-time behavior of the underwater networked control system is evaluated realistically using our proposed integrated cosimulation environment, which includes different simulators. Our performance results indicate that under calm water conditions, our proposed hybrid system reduces the docking time by 33% compared to the acoustic-only.

Key words: Underwater communication, autonomous underwater vehicle, acoustic, networked control system, MAC, cosimulation

1. Introduction

An autonomous underwater vehicle (AUV) is an underwater robot that works independently of an operator. An AUV can control the thrusters and propellers as well as operate sensors with an onboard computer and power supply to move the vehicle through the water to perform predefined critical missions. To perform complex underwater operations swarms of AUVs can cooperate to undertake missions that are hazardous for divers. AUVs' use permits a high level of accuracy for applications and requires precision such as military missions, archaeology, and underwater infrastructure monitoring and maintenance. These operations require high data

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rate communication between AUVs and base station.

Networked control systems (NCSs) are distributed systems, where controller and sensor functions of feedback control system are performed by different nodes, which exchange messages among themselves over a communication network [1]. NCS approach has been especially preferred over conventional control systems, and extensively employed in industrial applications, due to reduced complexity and cost [1]. Underwater NCSs, involving communication and control of AUVs require reliable high-speed network communication among underwater vehicles. Successful implementation of underwater networks has been realized by using optical waves, acoustic waves and radio frequency [2].

Underwater communication systems mostly use acoustic technology, since lower frequency waves suffer less from the absorption loss. The acoustic waves used in underwater acoustic communication are low-frequency signals with long wavelengths. Hence they can traverse long ranges in the order of kilometers for relaying information [2]. Acoustic communication is a proven technology for deep underwater as well as shallow water. However, for shallow water applications it is severely affected by the time-varying multipath effect and high levels of ambient noise due to waves and other movements [3]. Although there are some works such as [4] for decreasing the end to end delay among AUVs using acoustic links, the data rate and propagation speed of acoustic channel are not sufficient for emerging applications like docking at an underwater base and controlling swarms of AUVs. For the precise control and coordination of AUVs, a high data rate and short sampling time are required.

Radio frequency (RF) communication provides high data rates and low propagation delay under the water without the line of sight requirement [5]. However, under the water, RF waves suffer from higher and frequency dependent absorption, which causes higher path loss, limiting the range of operation and requires careful calibration of frequency, antenna design and transmission power [6]. To address these issues, authors in [7] developed RF path loss models in different underwater conditions. Propagation of RF waves from air into freshwater was studied in [8], and an optimum frequency range of 3–100 MHz was found for sending signals to a depth of 5 m. As research in underwater RF communication is evolving, MAC schemes are also being studied. In [9], ALOHA and CSMA are compared, concluding that CSMA without acknowledgment is the most appropriate MAC for an underwater RF network with low traffic.

Optical wave is another technology that can offer remarkably high data transmission rates for underwater communication. Campagnaro et al. [11] proposed a multimodal optical and acoustic control system for underwater communication that allows the underwater vehicle to perform its mission. Additionally, they have offered proactive switching by applying a signaling mechanism to enable more reactive switching between acoustic and optical modes. To evaluate the performance of the multimodal acoustic and optical system, an inspection-class hybrid ROV/AUV was simulated in DESERT simulator considering the application layers. Similarly, in their recent work [10] considering the remote control design, Campagnaro et al. have investigated several wireless communication technologies such as acoustic, optic, RF, and magnetic induction (MI) and described their pros and cons for underwater communication. Furthermore, they evaluated AUVs' achievable quality of service (QoS) in a simulated underwater environment. Moreover, according to the autonomy level of the vehicle, control requirements for different applications, such as navigation, positioning and real-time video streaming are proposed.

In this work by taking into account the data rate constraint of acoustic communication and close range limitation of RF link, we propose a novel NCS for controlling AUV to perform docking maneuver by employing

hybrid acoustic and RF communication. In the considered networked control scenario, the AUV location is remotely measured by a fixed docking station equipped with distance measuring sensors and transmitted to the AUV using the proposed hybrid communication network. The system uses the acoustic mode for long distances, which is greater than a threshold distance in this paper, and when it approaches the vicinity of the docking station (i.e. RF range) it switches to the RF mode. These messages provide the required information for the navigation of AUV. Low speed and large delay characteristic of the acoustic signals led to low control gains that are insufficient for precise navigation. However, employing high sampling frequency and high data rate of the RF mode at the proximity of the docking station enables accurate docking maneuvering. Furthermore, we assess the effects of water currents on the underwater networked control system communication for the AUV navigation and demonstrate how the NCS is effected via changes in the communication model and characteristics of the water.

Dynamic behavior of the underwater environment and movement of the AUVs are simulated realistically using UUV simulator, whereas hybrid communication framework including the channel characteristics, protocols, control algorithm and continuous dynamics are modeled via True-Time and simulated using real-time embedded computers. To the best of our knowledge, this is the first research that demonstrates an integrated cosimulation environment for testing underwater networked control applications taking into account full dynamics of the system and controlling AUVs in a networked control framework using hybrid acoustic and RF communication. In this work, via detailed simulations, the performance of the proposed hybrid system and the acoustic-only system has been investigated in terms of time to dock, cumulative error, communication energy and motive energy considering both a calm water scenario and a realistic scenario modeling water currents effects.

The rest of the paper is structured as follows: Section 2 presents the proposed hybrid communication framework for the underwater networked control system. Section 3 provides the details of considered underwater communication protocols and channel modeling. Integrated cosimulation environment for underwater NCS is presented in Section 4. Section 5 involves our simulation experiments and results. Conclusions along with further discussions are presented in Section 6.

2. Hybrid communication and control framework for underwater networked control system

The docking station is positioned on the seafloor, to provide a safe place for keeping AUVs, charging their batteries and transmitting collected data via a high data-rate wired link. Our docking scenario is based on the omnidirectional system in which AUV can enter to docking station from any direction. However, docking an AUV in the sample space of docking needs high precision to ensure that AUV does not damage the docking station. Figure 1 depicts a scenario in which an AUV performs a docking maneuver while the rest of them move around the docking station. To utilize advantages of the both RF and acoustic waves for better navigation of AUVs, we propose a hybrid communication system in which for long-distance acoustic communication is employed and for short ranges RF communication is performed. Figure 2 depicts a block diagram of the system in which acoustic and RF links used on the networked control system are specified.

AUVs usually are not equipped with a positioning system due to the high complexity and weight of such equipment. However, we can take advantage of the NCS for solving this problem. For this purpose, a message regarding the position information is broadcasted periodically by the docking station to all AUVs, using a position detection device called ultrashort baseline (USBL) [12]. Upon receiving these messages and using an onboard implemented feedback control algorithm, the error is measured and required force and torque is generated to be applied to the AUVs propellers.

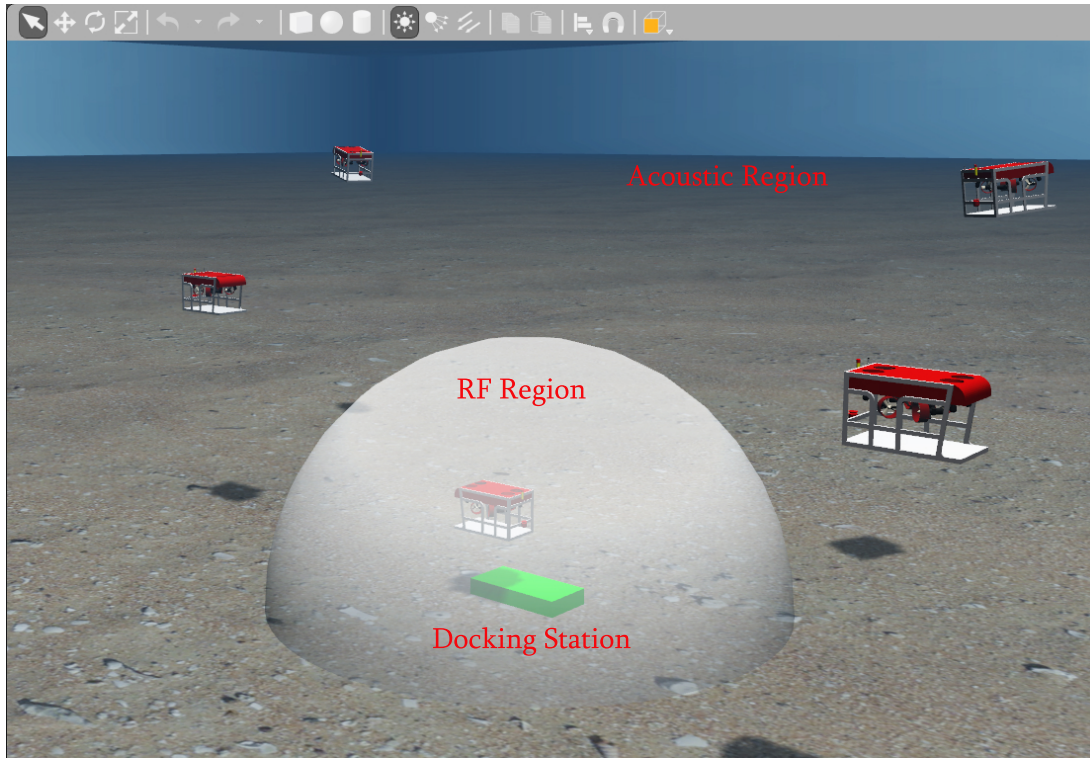


Figure 1. Acoustic and RF operation ranges of multiple AUVs with respect to the docking station. The point of view is underwater.

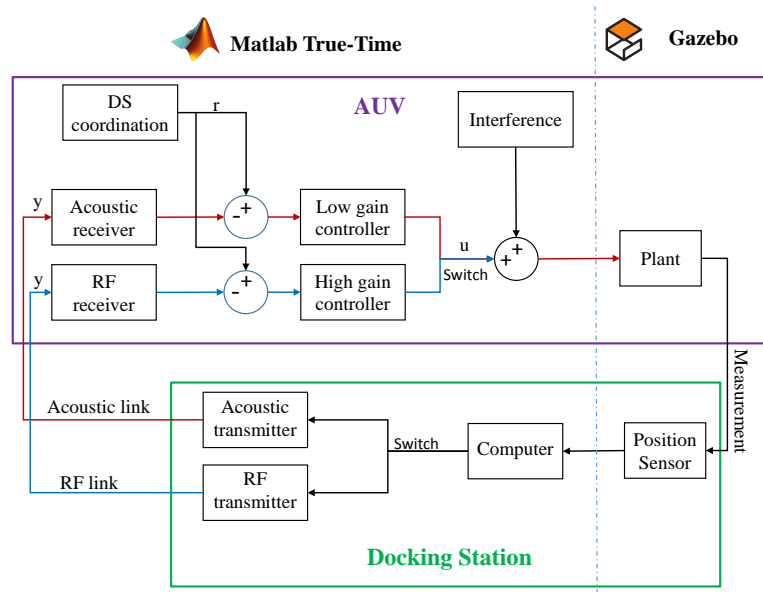


Figure 2. Block diagram of the proposed hybrid networked control system.

For successful docking, the communication between the AUVs and station should be reliable. Regardless of operating mode, the docking station always initiates the communication by transmitting a packet with initial

transmission power. If an AUV did not receive the signal by the expected time (e.g., due to fading), the required power level for correct reception of the signal is calculated by AUV and transmitted to the docking station. Therefore, by adjusting the transmission power, the docking station tries to improve the reliability of communication.

2.1. Control model for AUVs

For steering the AUV and damping its response, we have implemented a proportional integral derivative (PID) controller for controlling the orthogonal axis of the AUV during its cruise. Pitch and roll control run as local control loops based on onboard sensors, depth, forward motion and yaw is controlled based on the position data received over the network, and lateral movement is uncontrolled and is governed by the hydrodynamic forces. A discrete time approximation of the control loops are implemented as described in Equations (1)–(3) below:

$$e(kt_s) = r(kt_s) - y(kt_s) \quad (1)$$

$$P(kt_s) = K_p e(kt_s) \quad (2)$$

$$D(kt_s) = \frac{T_d}{T_d + Nt_s} Dt_s(k-1) - \frac{KT_d N}{T_d + Nt_s} (y(kt_s) - yt_s(k-1)) \quad (3)$$

$$I t_s(k+1) = I(kt_s) + \frac{K t_s}{T_i} e(kt_s) \quad (4)$$

$$u(kt_s) = P(kt_s) + D(kt_s) + I(kt_s), \quad (5)$$

where $r(kt_s)$, $y(kt_s)$ are the desired and measured values of the control at k^{th} multiple of the sampling period t_s , and their difference $e(kt_s)$ represents the position and orientation error. The proportional, derivative and integral terms of the PID controller are calculated separately using Tustin's approximation [13] in Equations (2)–(4). Moreover, the gains of each term of PID controller (i.e. proportional gain K_p , derivative gain KT_d , and integral gain $\frac{K}{T_i}$) at each NCS loop and the sampling period t_s are determined periodically based on the communication mode and protocols. Separate onboard controllers for acoustic and RF links calculate the control input for each axis of the AUV. Receiving position information from the docking station, the AUVs compute the control signal $u(kt_s)$ using Equation (5) for commanding thrusters.

3. Communication protocols for underwater networked control system

In the implementation of the network protocols in our simulation, packets carry the control information between the docking station and multiple AUVs. The packet transmitted from the docking station includes fields such as receiver ID, position, reference position, and time stamp and has a length of 512 bits. On the reverse link, the packet sent from the AUVs has 64 bits and it involves the node ID and data fields. In the following subsections, we present the power control mechanism and medium access protocols for the hybrid acoustic and RF underwater networked control system as well as corresponding channel models.

3.1. Medium access schemes for acoustic mode

We have considered two different periods for the frame time of MAC protocol in acoustic mode, as depicted in Figure 3. While the docking station uses the first downstream frame time to broadcast the message to the AUVs, the second period is used by AUVs as an upstream channel that we propose to implement one of TDMA (TD), slotted ALOHA (SA) and waiting room (WR) protocols as shown in Figures 3a–3c. To

perform docking maneuver successfully in the NCS, the position information of all AUVs needs to transmit periodically. Therefore, the TDMA scheme is assigned for the downstream channel to transmit messages to the AUVs sequentially. Through these messages, while an intended AUV captures its location information to implement its move towards the docking station, all other AUVs can also receive the same packets and learn about the other AUVs' location which helps them to avoid physical collisions among the vehicles. To ensure that all packets from AUVs are received correctly, a short delay time equal to maximum propagation delay is added at the beginning of docking station's period.

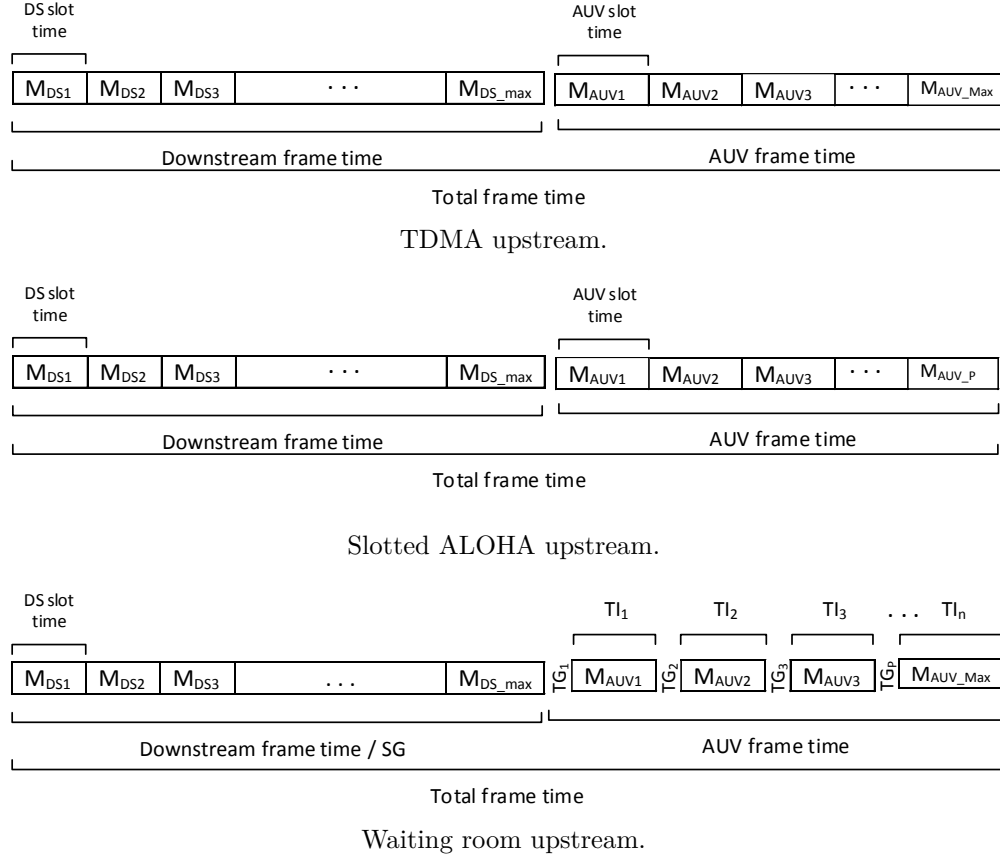


Figure 3. Frame structure and MAC schemes for acoustic mode.

3.1.1. Frame time for acoustic mode

Propagation delay is the main reason for the long delay in acoustic communication. This delay is the source of phase delay and it should be incorporated carefully in the distributed design of the control loop of NCS. According to the maximum number of supported vehicles (i.e. V_{MAX}), the frame time for AUVs and docking station is designed. The length of message, M_{DS} , and data rate of the acoustic modem, R_{AC} , are also considered in calculating frame time, so that, the slot time for the docking station found as, $DS_{SL} = M_{DS}/R_{AC}$ and total frame time of docking station is calculated as $TF_{DS} = DS_{SL} * V_{MAX}$. The number of bits in the message M_V and propagation delay of acoustic signal v_{AC} should be considered in calculating the slot times and total frame time of the AUVs, i.e. TF_{AUV} . Hence each AUV's slot time can be obtained as $T_{SV} = M_V/R_{AC} + d/v_{AC}$,

where d is the distance from docking station. Multiplying T_{SV} by the maximum number of vehicles, V_{MAX} , determines total AUV frame time. Finally, a summation of AUV and docking station frame times will give us the MAC protocol's total frame time as follows: $T_F = TF_{DS} + TF_{AUV}$. Values for the above calculations are demonstrated in section 5.

3.1.2. Time division multiple access (TDMA)

TDMA allocates for each vehicle a separate duration equals to the AUV slot time for transmitting using the acoustic upstream channel to the docking station. TDMA frame time is depicted in Figure 3a. In this scheme total number of slots is determined as $N = V_{MAX}$.

3.1.3. Slotted ALOHA

The upstream AUV period in S-ALOHA starts after waiting for guard time of propagation delay, following the downstream period. The guard time is added to ensure that the last AUV has received the packet from the docking station and to synchronize all AUVs. In this scheme, some percentage of propagation delay should be considered in calculating AUV slot time [14]. Therefore 70% of additional transmission time and propagation delay is assigned for AUV slot time. The total number of the slots is set to P and $P \leq N$, where N is the total number of AUVs.

3.1.4. Waiting room protocol

In this scheme, a different terminal gap (TG) value is assigned for each AUV with transmission interests. Furthermore, each AUV has a transmit interval (TI_i), which is the limit for the AUV transmission duration. A synchronization gap (SG) time is also set for all of the nodes. The protocol works as follows: During the SG, there are no transmissions on the network and the nodes commit for transmissions in the current frame. At the end of SG, each node starts a countdown timer of TI_i and wait for it to expire. The node with the shortest TI expires first and it starts transmission. All other nodes pause their timers until the end of a transmission. The process repeats until all committed nodes complete their transmissions, and no more transmissions start, which signals the SG of the next frame Figure 3c. In our case, SG coincides with the downstream period, where the docking station transmits.

3.2. Acoustic channel model

Undoubtedly one of the harshest environments for data transmission is the underwater acoustic communication channel. For the long distances, the optimal channel capacity is less than 50 kbps for signal to noise ratio (SNR) of 20 dB by using an ordinary modem with the data rate of less than 10 kbps [15]. A contemporary commercial underwater acoustic modem, like EvoLogics *S2CR48/78* at the range of 1000 m, can offer a data rate up to 31.2 kbps. Channel frequency, chemical and physical properties of the water and the shape of the environment affect the acoustic propagation in water. Spreading loss and absorption loss are two main reasons for a path loss on the acoustic channel [15]. The expanding area that acoustic wave covers while it propagates from the transmitter is the reason for the spreading loss as given in Equation (6) as follows:

$$PL_{sp}(r) = k \log(r), \quad (6)$$

where k represents the spreading factor and r is the distance.

In contrast, absorption loss is due to losing signal in the form of thermal energy because of friction and ionic relaxation of the acoustic signal propagation from a projector to hydrophone in the water as given in Equation (7) as follows:

$$PL_{ab}(r, f) = 10\log(\alpha(f))r, \quad (7)$$

where absorption coefficient, α is affected by the characteristics of the water and considering the frequency of an acoustic wave (i.e. f) it can be calculated using Thorp's expression as:

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75 \times 10^{-4}f^2 + 0.0033, \quad (8)$$

where f is the frequency of acoustic signal in KHz. Adding the spreading and absorption losses the total path loss can be determined as:

$$PL(r, f) = PL_{sp}(r) + PL_{ab}(r, f). \quad (9)$$

Before applying the fading we subtract the path loss from the transmitted signal $P_t(\text{dB})$ to determine the received power in dB as:

$$P_r(\text{dB}) = P_t(\text{dB}) - PL. \quad (10)$$

Multipath and noise are the main obstacles in acoustic communication. We assume flat fading in this work, where all multipath components arrive at the receiver with similar delays. Therefore, Rayleigh fading is adopted to model the variations due to multipath. Thus the received power is exponentially distributed, where the power level calculated in (10), converted to watts is the mean of the exponential distribution. To distinguish the received signal correctly, the received power should be above a threshold, and considering acceptable signal-to-noise ratio (SNR).

3.3. RF channel model

Although RF signal has a high data rate and high propagation speed, it severely suffers from high path loss in underwater communication. For a 10 MHz signal, in a freshwater environment, the maximum achievable data rate is about 3 Mbps [6]. The path loss for the RF channel is extremely affected by the conductivity, permittivity and permeability of water. Neglecting the air-water boundary loss, the path loss can be calculated [16] as:

$$PL = RE(\gamma) \frac{20}{\ln(10)} r, \quad (11)$$

where RE reflects real part, r denotes distance; γ is propagation constant given by:

$$\gamma = j\omega \sqrt{(\mu\epsilon - j\frac{\sigma\mu}{\omega})}. \quad (12)$$

Here ω is the frequency in rad/s, ϵ denotes the total permittivity of water, μ stands for the permeability of free space, and σ represents water's conductivity [16]. Finally, the total path loss equation can be obtained by using Equations (11) and (12) as follows:

$$PL = RE(j\omega \sqrt{(\mu\epsilon - j\frac{\sigma\mu}{\omega})}) \frac{20}{\ln(10)} r. \quad (13)$$

The average received signal power is calculated by considering the above path loss formulation for the RF channel, and Rayleigh fading is applied as exponentially distributed power, as in the acoustic channel, followed by the SNR is calculated.

4. Integrated cosimulation environment for underwater NCS

Considering the harsh environment where AUVs operate to achieve a mission, utilizing proposed integrated cosimulation considerably decreases the time, cost and risk of a mission by reducing the number of trails to obtain optimal values [17]. For this purpose, we have developed an integrated cosimulation environment of the hybrid RF and acoustic underwater networked control system, for implementing the docking maneuver application. The physics is simulated in a realistic manner by Gazebo [18], whereas the control and communication protocols simulation is provided realistically in Matlab True-Time. By creating such a design, we have employed the best properties of the different simulators. For a realistic simulation environment for NSC, we have employed Gazebo which makes it possible to implement complex robots in modeled dynamic environments in realistic scenarios. Furthermore, within Gazebo, we have employed UUV simulator [19], which is a simulator explicitly designed to model underwater dynamics [20] accurately. UUV simulator can realistically simulate unmanned underwater vehicles, including the AUVs and ROVs, considering the external disturbances, hydrodynamic and hydrostatic effects of water.

4.1. Cosimulation approach

In this work, robot operating system (ROS) [21] is used to provide us a flexible framework for programming and modeling robots and controlling their operations. However, ROS lacks realistic models of communication physics and protocols and models of real-time embedded computers. To augment these areas, the True-Time toolbox of Matlab Simulink has been employed in this work. Executing the source code of the actual model in the embedded computers of True-Time helps schedule the tasks for coordinating different parts of the cosimulation environment. Moreover, True-Time supports simulation of wireless networks in the MAC layer and supports several built-in communication protocols with extension possibilities.

Providing a cosimulation environment by integrating the aforementioned simulators is one of the main contributions in this paper. Figure 4 depicts a workflow of the messages and interaction of different components as well as a detailed model in the Simulink. Our goal is to incorporate different cosimulation modules to provide an environment for developing and testing different missions performed autonomously using the underwater networked control system. However, synchronization of Matlab True-Time and Gazebo is an issue in cosimulation as they both apply dynamically variable time steps in their solvers, causing their simulation time to progress in different time steps. To synchronize different simulators' clock time, we use the messaging capabilities of ROS. Once two simulators are initialized, True-Time employs Gazebo's clock for updating its timer. Determining the AUVs' position, controlling their movement and attitude, as well as the communication network and links, are modeled using True-Time.

The Matlab True-Time model is depicted as the inset in Figure 4. The block labeled "AUV" implements the onboard real-time computer in the level of detail of source code execution. The actual source code that will run on the AUV is executed over this block. The blocks labeled "Acoustic Network" and "RF Network" provide communication and packet delivery models over acoustic and RF links between the vehicles and the docking station. The communication links model both the MAC protocol and the physical layer, so that physical effects, such as path loss considering the instantaneous position of the vehicle with respect to the docking station,

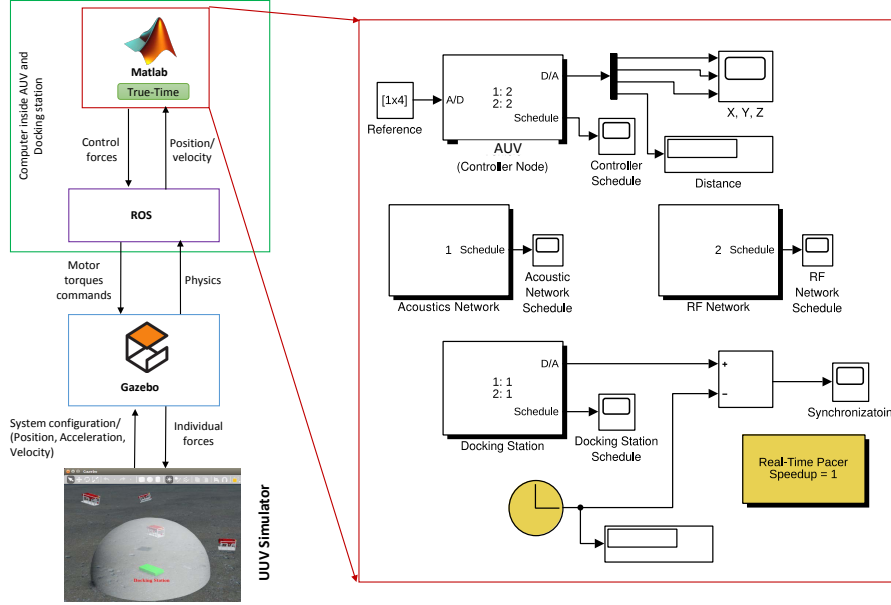


Figure 4. Workflow and Simulink models for proposed cosimulation framework.

and physical characteristics of water such as salinity can be implemented in the simulator. The block labeled "Docking Station" at the bottom of Figure 4 implements the docking station's real-time embedded computer. This block is responsible for employing the position sensor to determine the AUVs' location and sending position data to the AUVs.

5. Performance analysis

In this section, we present the performance analysis of the proposed hybrid networked control system compared to the acoustic-only system by presenting simulation results for performing docking maneuver in the calm water scenario (ideal case) and in the presence of water currents.

To evaluate the performance of the proposed system, the metrics that we used are time to dock, motive power, cumulative error, and communication energy, which are considered as the common metrics in these types of applications [6]. Here time to dock represents a measure of how long it takes for an AUV to reach 2% of the target distance. Motive power is defined as the required force that is used for moving the AUV. Communication energy metric is the total energy consumed by an AUV to send and receive all (data and control) packets and cumulative error is the area between the docking station position and the AUV position (i.e. the integral of positioning error).

5.1. Simulation settings and parameters

To model the communication channel, our simulation setup is based on the following parameters. We have applied parameters of EvoLogics S2C R48/78 and WFS seatooth S300 parameters for underwater acoustic and RF modem, respectively. For motive energy calculations we have assumed the parameters of NeuMotors 1925-3Y. Maximum motive power is taken as 546 W. The MAC protocols are designed for 8 AUVs (i.e. $V_{MAX} = 8$). Table 1 represents the parameters for MAC scheme design which are based on subsection 3.1.1.

The docking station is positioned at $[0, 0, -100]$. In total, there are 5 vehicles in the simulation, 4 of them are located at the position of 50 m away from the docking station and they are kept hovering in that position. The arbitrary initial position of the AUV which will perform the docking maneuver is $[-20, 20, -75]$. At the start of the simulation, only the acoustic link is active. AUVs receive packets from the docking station over an acoustic link. If they receive a message within an expected time interval, they accept the message and use the contents. Otherwise, they calculate the required signal power for proper reception and transmit it to the docking station. When the AUV reaches 15 m distance from the docking station, it sends a “turn on RF” message in the upstream phase. The RF link is activated exclusively and controls the AUV through a high gain controller when it is closer than 10 m to the docking station. The high gain is possible because of the reduced delay in the control loop which affords better stability. The simulation parameters which we used are presented in Table 2. It also includes the parameters that have been used for calculating the path loss characteristics. After path loss, Rayleigh fading is applied to obtain the instantaneous received power level.

Table 1. Different MAC scheme parameters.

| Parameters | Value |
|--|----------|
| Docking station message length M_{DS} | 512 bits |
| Acoustic modem data rate R_{AC} | 10 Kbps |
| Docking station total frame time TF_{DS} | 0.4096s |
| AUV message length M_V | 64 bits |
| Distance to the docking station d | 50m |
| Acoustic wave speed v_{AC} | 1500 m/s |
| AUVs total frame time TF_{AUV} using TDMA | 0.034s |
| AUVs total frame time TF_{AUV} using slotted ALOHA | 0.030s |
| Transmit interval in waiting room TI | 0.01s |
| Terminal gap in waiting room TG | 0.030s |
| Max number of slots for slotted ALOHA (P) | $N = 8$ |

Table 2. Simulation parameters.

| Parameters | Acoustic | RF |
|----------------------------------|-------------------------|---------------------------------|
| Carrier frequency | 100 KHz | 10 MHz |
| Data rate | 10 Kbps | 3 Mbps |
| Frame time | 0.74 s | 0.04 s |
| Signal power limit | 4.5 W | 3 W |
| Circuit power P_c | 1.1 W | 4.5 W |
| DS Packet time t_{ds} | 3.84×10^{-2} s | 0.28×10^{-4} s |
| Sampling period t_s | 0.74 s | 0.04 s |
| Proportional gain $K_p[x, y, z]$ | [75, 75, 225] | [155,155,455] |
| Integral gain $K_i[x, y, z]$ | [10, 10, 10] | [195,195,195] |
| Derivative gain $K_d[x, y, z]$ | [65,65,55] | [270,270,55] |
| Derivative time T_p | 0.74 | 0.04 |
| Spreading factor k | 1.5 | N/A |
| Threshold | 1.9mW | 2mW |
| Permittivity ϵ | N/A | $80(8.854 \times 10^{-12}) F/m$ |
| Permeability μ | N/A | $4\pi \times 10^{-7}$ H/m |
| Conductivity σ | N/A | 0.01 S/m |

5.2. Result

The goal for an AUV is to reach the docking station as quickly as possible and to perform precise docking. For this reason, time to dock under various water conditions and communication protocols is a good performance measure. The distance vs. time graph of a typical docking maneuver of an AUV for different protocols is shown in Figure 5. We aim to quickly perform landing on the docking station without overshoot and steady state error despite the physics of the water.

Figure 5 shows the performance of the three protocols in calm water; the proposed hybrid system uses solid lines, and the acoustic-only system uses dotted lines. The time to dock metric is introduced to measure how long it takes for an AUV to reach 2% of the target distance. Figure 5a demonstrates that the AUV using the proposed hybrid system with the TDMA protocol can reach the docking station in about 102 s which is shorter than the acoustic-only system which takes about 140s. Similarly, in Figures 5b and 5c, we can observe that time to dock for the hybrid system is considerably less than the acoustic-only system. This is due to the fact that the AUV switches to the high gain controller offered by the RF link and utilizing increased sampling frequency enables the AUV to apply a more aggressive control effort; therefore, the final approach is quicker and more precise than the acoustic-only controller.

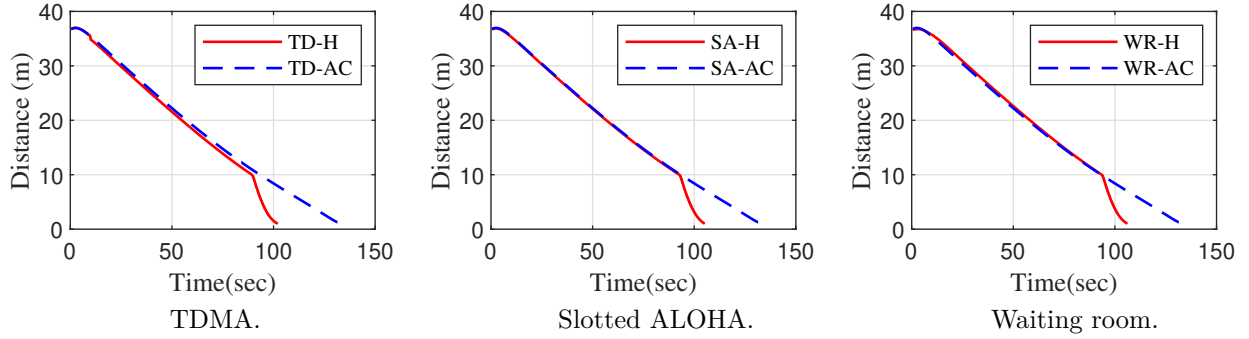


Figure 5. Time to dock of the AUV for acoustic-only (AC) and proposed hybrid (H) systems using TDMA, S-ALOHA and Waiting room, for the calm water scenario.

Time to dock is an essential parameter in the performance; however, it may come at the cost of high energy requirements. Moreover, we believe that our method is a good hybrid approach where high power is only required towards the end of the docking maneuver. These results show the performance of our method from that perspective.

Figure 6 depicts the motive power of thrusters over the docking time. To calculate the motive power, the thruster output is multiplied by the AUV velocity. The output of the thruster is calculated by multiplying the control signal u by a constant value, which relates the thrust force to the control signal. Hence using $F_m = u/1.17$, gives us the output of thruster and motive power is calculated by $P_m = F_m \times v$ where v is the velocity of AUV. This provides instantaneous power and by integrating motive power over the time we can determine the motive energy. Low control effort in Figures 6a–6c indicates that initially, only the low gain controller is used during acoustic communication. When an AUV approaches the RF operating region, the proposed controller switches to the high gain controller, which affords faster response control signals for navigating AUV toward the docking station, but at the expense of much higher motive power. This can be verified by a short term rise in all three communication protocols in Figure 6.

High water currents cause AUV to experience difficulty in approaching the docking station and making

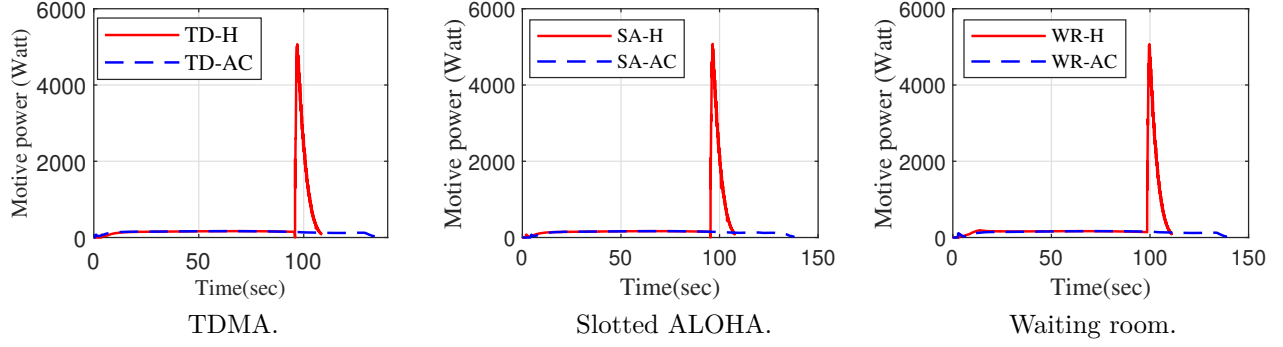


Figure 6. Motive power of AUV for acoustic-only and proposed hybrid systems using TDMA, S-ALOHA and waiting room for the calm water scenario.

precise maneuvers in its vicinity. Since water currents cannot be avoided during real-world operations it is crucial to verify their effect on the operation of the vehicle.

To consider the realistic underwater conditions of oceans and seas, we have applied disturbances to the modeled AUV in the form of water currents. Figure 7a shows that the AUV using TDMA based acoustic-only system has time to dock of about 138 s when there is zero disturbance, but as the disturbance is increased to 0.15 m/s, the AUV cannot reach the docking station during the allowed simulation time of 300 s. The value 300 s represents that although AUV can approach the docking station's vicinity, it cannot perform docking successfully due to water currents. The AUV using the hybrid system with TDMA protocol, on the other hand, has time to dock at about 105 s, which is 32% faster than acoustic-only under zero disturbance. Although the performance worsens with increasing disturbance, compared with the acoustic-only system, the proposed hybrid system, due to faster control, can tolerate increasing current velocities of up to 0.35 m/s. For current values higher than 0.35 m/s, since the AUV cannot reach the RF region, the hybrid system could not accomplish the docking maneuver as well.

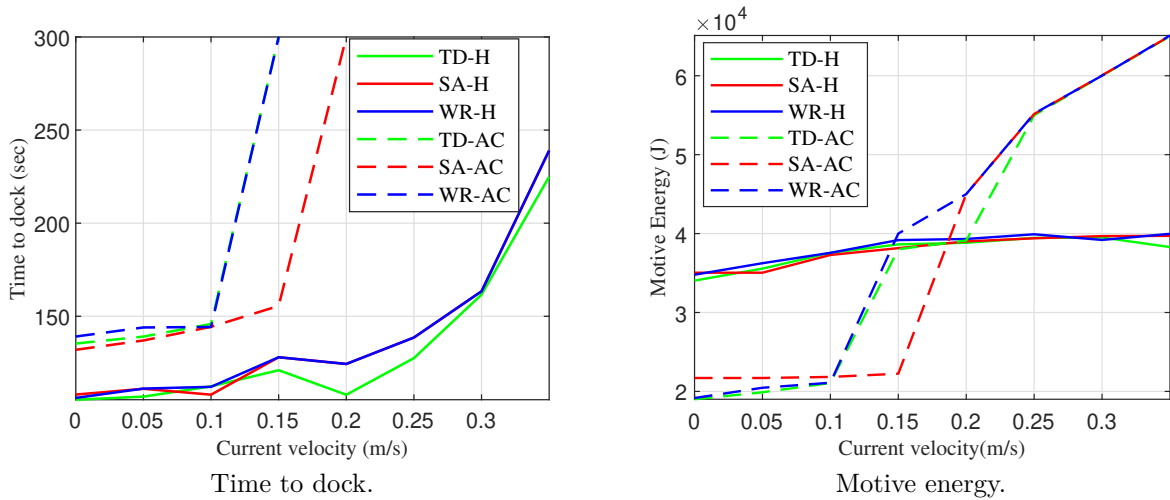


Figure 7. Time to dock and motive energy of AUV w.r.t increasing velocity of the water currents for acoustic-only and hybrid system using TDMA, S-ALOHA and waiting room protocols.

By applying currents to the system, Figure 7b shows the motive energy used by the AUV during docking maneuver for the acoustic-only and hybrid system using TDMA, S-ALOHA and waiting room protocols. Using both acoustic-only and hybrid systems, the motive energy of AUV increases slightly with increasing velocity of water currents as the controller has to apply a larger force to counter opposing disturbance force. The motive energy of AUV using the hybrid system is 61.48% larger than that of the acoustic-only systems for S-ALOHA, as the controller in the RF region applies larger force to increase the velocity of the AUV. The higher motive energy of AUV using a hybrid system enables the AUV to have significantly lower time to dock and smaller cumulative error as compared to the AUV using the acoustic-only system.

Cumulative position error is defined as the sum of the absolute value of the distance between the reference position and actual position of the AUV, summed up over every sampling time of the simulation run.

Figure 8a demonstrates the cumulative error averaged over 10 simulation runs, for hybrid and acoustic-only systems under increased water currents. Initially, an almost linear increase can be observed, followed by a sharp increase in the acoustic-only system using TDMA and waiting-room at the velocity of 0.1 m/s, and for the S-ALOHA protocol at velocity 0.2 m/s. This can be explained by the fact that although the AUV can approach the docking station, it cannot complete the docking maneuver with low control gains. As a result, the cumulative error keeps increasing until the allocated simulation time expires at 300 s. In comparison to acoustic-only systems, the hybrid system with three different MAC protocols has smaller cumulative errors. The cumulative error of S-ALOHA hybrid system is 16.67% less than S-ALOHA of acoustic-only system which gives the least cumulative error for an acoustic-only system. Furthermore, waiting room and S-ALOHA have about 8.2% and 7.91% less cumulative error respectively, on average. Hence, it can be concluded that TDMA gives the most stable performance under increasing the velocity of water currents.

Although motive power is important, total communication energy also deserves extra attention because communication overhead is introduced to the system.

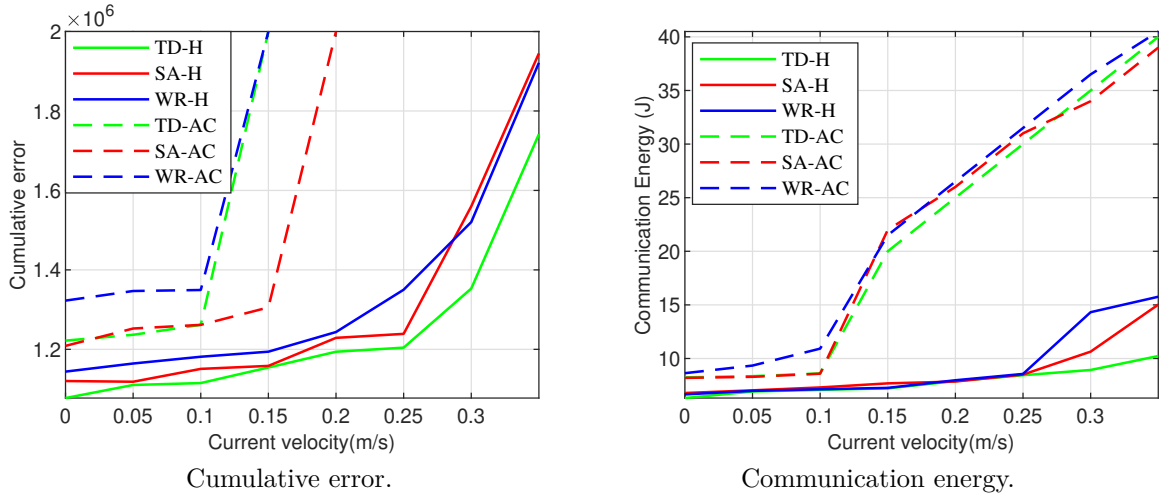


Figure 8. Cumulative error and communication energy of AUV w.r.t increasing velocity of the water currents for acoustic-only and hybrid system using TDMA, S-ALOHA and waiting room protocols.

Figure 8b represents the communication energy of AUV with respect to water current velocity. The energy consumption of the AUVs using an acoustic-only system increases marginally with increasing disturbance. However, when the velocity reaches about 0.15 m/s there is a sudden rise in the communication energy of

AUV due to its attempt to approach to docking station but failing to make headway due to currents and communication energy consumption keeps increasing. We can observe that S-ALOHA and TDMA in acoustic-only spend about 26% less energy for communication than the waiting room. There is also a steady rise in communication energy for the hybrid system by increasing the velocity which is on average 20.6% less than acoustic-only. When velocity reaches 0.25 m/s we can observe a sharp increase in the communication energy especially in S-ALOHA and the waiting room which is 33.16% and 39.12% on average respectively. We can conclude that the hybrid system using TDMA protocol has the least communication energy among all.

6. Conclusion

In this paper, we have developed a novel underwater networked control system using hybrid acoustic and RF links to satisfy the requirements of docking maneuver application for AUVs. The proposed framework can be used for any other underwater vehicle based NCS application that needs to operate autonomously with high precision.

We have implemented detailed simulation models of acoustic and RF underwater channel characteristics. We have also developed a novel cosimulation environment modeling the AUVs with real-time embedded computers with realistic online communication. This helps us to study the hydrodynamics' physics on AUV trajectory and accurately model the underwater environment. Besides, we have implemented adaptive MAC schemes and adaptive controllers that can respond to changing data rates. Furthermore, in this cosimulation environment, we have conducted various simulations to verify the disturbing effects of water currents on controlling AUVs performance.

We have shown that employing hybrid acoustic and RF communication rather than acoustic-only is not only feasible for controlling underwater vehicles but also more beneficial. We also found that under calm water conditions, the hybrid system reduces the docking time by 33% due to the higher control gains that RF controller affords. Furthermore, subject to depth dependent disturbance, the acoustic-only system fails to approach the docking station, while our proposed hybrid system can withstand hostile forces and complete docking. Although the hybrid system's communication energy at low water current is smaller than that of the acoustic-only system by up to 34%, this amount grows by increasing the speed of water current. However, to improve the docking time, the hybrid system consumes up to 78% higher motive energy as compared to the acoustic-only system. Furthermore, in the realistic scenario with water currents faster than 0.15 m/s, the acoustic-only system cannot perform docking maneuver, while our proposed hybrid system can cope with increasing velocity until 0.35 m/s and perform docking maneuver successfully.

These performance gains are the direct result of decreased communication delay in the RF region, which allows high control gains.

Acknowledgment

The research leading to the presented results has been undertaken within the SWARMs European project, under Grant Agreement n. 662107-SWARMs-ECSEL-2014-1, partially supported by the ECSEL JU.

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