On the Feasibility of Fully Wireless Remote Control for Underwater Vehicles

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***Abstract*—In this paper, we explore the possibility of controlling a Remotely Operated Vehicle (ROV) via a fully wireless control channel. As a first step, we review the expected bit rate offered by optical, acoustic as well as radio-frequency underwater communication technologies, as a function of the distance between the transmitter and the receiver. We then discuss the ROV data transfer requirements and discuss which ones can be supported by a given technology at a given distance. Finally, we simulate the performance of the system during missions of interest, and conclude by discussing the effectiveness of wireless control methods for ROVs.**

I. Introduction and Related Work

Nowadays, Remotely Operated Vehicles (ROVs) are used in order to monitor the underwater environment and man-made assets. Usually, ROVs are controlled through a cable, called umbilical, which conveys power supply and data connections to the ROV, making it possible to manage the system in real time. However, the umbilical inherently limits the mobility of the ROV due to cable strain and entanglement risks. Wireless ROV control would help avoid such issues by removing the need for a physical cable, at the price of an increased need for ROV power autonomy and smaller data rates. This paper offers our view on the feasibility of wireless ROV management. In particular, we start by relating typical services offered by ROVs (along with their required application-layer data rates) against the rates typically offered by optical, acoustic and radio-frequency (RF) communication technologies available to date. We proceed by identifying a number of operational modes which can be chosen as a function of range to support a given set of ROV services, from simple guidance and positioning, to tool control, up to real-time video streaming. Finally we focus on remote control via acoustic communications, and extend the DESERT Underwater framework [1] to reproduce the communication patterns between the controller and an ROV, and measure the capability of the ROV to follow a prescribed path as a function of the operational mode.

The remote control of underwater autonomous systems (both ROVs and AUVs) has received increasing interest recently. One of the earliest systems to achieve a practical rate of several tens of kbps is the FAU Hermes modem [2], which has been experimented for some years in ports and in very shallow water environments, which are among the typical scenarios for remotely-controlled ROVs. In [3] the authors show the possibility to transmit a real-time video within short reach (reporting a bit rate of 1.2 Mbps at a distance of 12 m in a pool) using acoustic communications. They propose to track and compensate the channel Doppler spread via a non-uniform resampling of the received waveform by adapting the resampling rate on-the-fly, as this makes it possible to remove most of the distortion that an OFDM signal experiences during underwater transmission. The target is to employ such a system for remote ROV control. In the same vein, the authors of [4] describe an acoustic communication system designed to provide a bit rate of 500 kbps at a distance of 60 m for an acoustic-controlled robot. The design is corroborated by field experiments. In [5] the authors investigate the acoustic networking of an AUVs with Autonomous Surface Vehicles (ASVs) to accomplish a common mission. After introducing the vehicle control architecture, the authors describe the acoustic communication and ranging capabilities of each node and finally show some experimental results obtained with two vehicles in the Douro river in Portugal.

Optical technologies for underwater transmissions are surveyed in [6], where the achievement of a 10-Mbps bit rate in a real experiment is reported. In [7] the authors describe their optical modem design, featuring six 470 nm LEDs arranged in a hemispherical geometry, and employed to transmit 10 Mbps OOK-modulated signals. The modem was tested in air, within a 15-m pool, and finally at a dock, with a TX/RX distance of 10 m, in conditions of minimal ambient light at night. The experimental outcomes validate the concept of omni-directional optical communication in water and suggest that transmission ranges greater than 100 m in deep water with rates of about 100 Mbps may be possible. In [8] the authors experimented real-time video transmission over a full-duplex optical link achieved via wavelength separation, at a distance of 15 m. In [9] the *Aquaflecks* optical modem is described. It embeds a 532 nm LED and achieves a maximum data rate of 320 kbps with an OOK modulation. The modem additionally equips an acoustic 30 kHz, 50 bps FSK transceiver, which can be employed, e.g., for ranging purposes. An AUV equipped with the same modem is also employed in a data muling experiment involving 8 Aquaflecks in a pool.

In [10], the authors summarize the issues related to the feasibility of underwater RF transmissions, and provide some examples of practical applications where radio frequencies are used. A discussion of RF communications in underwater scenarios with short-range monitoring and control purposes is provided in [11], where RF systems are also compared to acoustic and optical systems. However, the distance allowed by the RF technology is very limited, as even typical levels of salinity can heavily limit the propagation of RF signals.

In the following, we summarize the requirements of an ROV control system (Section II) and the feasibility of its wireless implementation in light of the capabilities of underwater wireless transmission technologies (Section III). Section IV details the simulation of an acoustic ROV control system designed in accordance with the observations in Sections II and III. Finally, Section V draws some concluding remarks.

II. Requirements for ROV Control

We start by introducing some realistic requirements for operational ROV control. These requirements will be checked against the capabilities of current wireless communications technologies in the next section, in order to infer an empirical relationship between distance and bit rate available for controller commands and ROV reports. We assume that control features can be divided into two classes, namely mandatory and optional features. Mandatory features include movement commands (both absolute and relative to the current position), management of the ROV's mechanical tools, feature toggling (e.g., lighting, sensing, etc.) and feedback from the ROV to the controller. In particular, the mandatory portion of the latter encompasses the ROV position estimate, tools status and sensor readings. Optional features include communication-intensive services. As a representative of this kind of services, we will refer below to live video streaming, which is a typically required ROV feature.

The encoding format for the information listed above is diversely implemented in different ROV models and control systems, which makes it difficult to find proper references for the amount of information transferred between the ROV and its controller. For this reason, we had to make some practical assumptions on the data representation format and on link-layer features such as coding redundancy for forward error correction. Based on these assumptions,[1] we define the following operational modes:

- **Mode 0** entails only the service of mandatory features and requires a minimum bit rate of about 2 kpbs;
- **Mode 1** adds very low quality slideshow-like video transmission, and requires a bit rate of 30 kbps;
- **Modes 2**, **3** and **4** progressively increase the video quality, starting from that of a low-quality mobile video-call up to a high-quality video, and require 64, 130 and 400 kbps, respectively;
- **Mode Video HD** provides HD-quality video streaming from the ROV to the controller, at a bit rate of 1.4 Mbps.

In the following section, we will discuss which underwater communication technologies make it possible to achieve the bit rate requirements defined above.

III. Wireless Underwater Technologies

The prominent technologies for underwater wireless transmission to date are acoustics, RF and optics. In this section, we survey commercial products and research prototypes based on these technologies, and provide some details on their expected performance. We consider a typical ROV control scenario where the ROV is located within about 150 m from the controller, and identify the transmission bit rate figures of each technology by relying on each system's data sheet. In doing so, we disregard those products that are explicitly targeted at some idealistic scenario[2] and rather focus on the ones that support normal operational conditions. In addition, among research prototypes, which often provide good performance and a high level of reliability but cannot be easily purchased, we will consider only those models that yield comparable or better performance with respect to commercial ones.

[1]The interested reader is referred to [12, Ch. 2] for more details.

[2]This includes, for example, fresh water RF modems, optical modems working in dark and clear waters, and acoustic modems for only-vertical links.

Table I
List of performance figures for some representative acoustic, RF, and optical underwater transmission systems

	Manufacturer and model	Range	Bit rate
Acoustic	LinkQuest UWM1000 [13]	350 m	17.8 kbps[1]
	EvoLogics S2C R 48/78 [14]	1 km	31.2 kbps[2]
	EvoLogics S2C R 18/34 [14]	3.5 km	13.9 kbps
	LinkQuest UWM3000H [13]	6 km	320 bps
	FAU Hermes modem [2]	150 m	87.7 kbps
Optical	Sonardyne BlueComm HAL [15]	20 m	5 Mbps
	Ambalux 1013C1 [16]	40 m	10 Mbps[3]
	SPAWAR optical modem [17]	2 m	10 Gbps
	Keio optical modem [18][4]	3 m	2 Mbps
	MIT low power led modem [19][5]	{6.5,8}m	{10,1}Mbps
	Penguin Automated Systems [6]	{11,15}m	{10,1.5}Mbps
RF	WFS Seatooth S500 [20]	10 cm	10 Mbps
	WFS Seatooth S300 [20]	{4,10}m	{156,25}kbps
	Koc University NWCL [21][6]	10 m	156 kbps
	WFS Technologies [10], [21][6]	0.2 m	10-100 kbps
	WFS Technologies [10][6]	50 m	1-10 kbps

[1] Worse results were obtained in Singapore's warm shallow waters [22].
[2] Better results were achieved in the Baltic Sea, worse results in Singapore's warm shallow waters [22].
[3] Experiments in [6] achieved 9.7 Mbps at 11 m in the Ontario lake.
[4] Results obtained independently by Keio and MIT.
[5] The values reported in [19] should be taken as a lower bound.
[6] Estimates resulting from theoretical analysis.

The most studied and used underwater telecommunication technology to date is based on acoustic signals, and provides sufficiently long transmission ranges compared to typical application requirements, fair reliability and robustness. However, the available bandwidth is very limited; in addition, horizontal transmission in shallow-water scenarios often results in poor, environment-dependent performance [11]. The upper portion of Table I reports acoustic modems yielding very different performance figures in shallow or very shallow water environments. In light of the requirements in Section II, we may conclude that acoustic communications are mainly useful because they support mandatory ROV features over long ranges. In addition, the prototype Hermes modem may be able to transmit a low-quality video over a range of about 100 to 150 m. In any event, the controller can operate between middle and long ranges, but only in modes 0 to 2.

The need for high speed communications under water has pushed the realization of optical devices that can transmit data within short distances at a bit rate on the order of one or more Mbps, e.g., [15], [16]. Some research prototypes are also being developed to improve such bit rates even further and possibly overcome the alignment and line-of-sight issues that are typical of optical modems [6], [7]. Turbid and shallow ocean waters represent a challenging environment for optical communication systems. In fact, high turbidity scatters and attenuates the optical field, whereas ambient light may become a significant source of noise, making transmissions close to the sea surface more difficult. In our review, we considered only the optical modems that have been tested in these conditions. For example, the Sonardyne BlueComm OATS [15] achieves a transmission rate of 20 Mbps up to a distance of 200 m, but only in deep, dark waters. For this reason, this model has not been considered in our review. The same applies to the optical modem implemented at WHOI [7], even though it should be noted that a similar technology is included in our review thanks to the collaboration between WHOI and BlueComm, as reported in [15]. Blue and green lights, which have a wavelength of 470 and 550 nm respectively, are the most used for underwater optical communication [17]. The middle portion of Table I lists some optical modems that, as expected, achieve very high bit rates at short range. For what concerns the requirements of our ROV control system, the commercial Sonardyne BlueComm HAL modem allows HD video monitoring for short range (Mode Video HD). Although the Ambalux 1013C1 High-Bandwidth Underwater Transceiver declares higher performance, its transmission rate depends very much on the environmental conditions.

RF communications can also achieve high transmission bit rates under water, although their communication range is still very limited. Indeed, the performance of RF modems is immune to most environmental conditions that affect the propagation of acoustic waves, including refraction-inducing temperature/pressure gradients, sea state, bottom sediments, etc. However, RF communications suffer from RF interference and are prone to very strong attenuation in salted waters, where the conducibility of the medium is larger than in fresh waters [10]. This can be seen from the bit rates declared for several RF modems and reported in the lower portion of Table I. Among the cited modems, those by WFS Technologies have been found to cover a broad range of applications at different ranges [20]. However, to cover larger ranges, they have to rely on a secondary acoustic communications unit. Theoretical analysis [10] shows that higher bit rates could be potentially achieved, although no experimentation is reported so far in this respect. The general conclusion that can be drawn from Table I is that RF modems are outperformed by optical modems at all typical operational RF ranges, with the only understanding that RF communications are omnidirectional, whereas optical communications are not.

Taking the best of all technologies in each range results in the bit rate vs. range graph shown in Fig. 1. We can observe that optical technologies are the preferred choice up to a distance of about 20 m, whereas acoustics would be the preferred choice from that point onward, due to the high bit rate that would be made available by the Hermes modem. Longer distances can be supported by EvoLogics modems operating at progressively lower frequencies. We also note that RF modems are consistently outperformed by optical or acoustic modems, and have the only advantage that RF transmissions are omnidirectional (unlike optical ones) and not prone to environmental characteristics (unlike acoustic ones).

After the considerations above and in light of the requirements in Section II, we can conclude that a fully wireless ROV control system should be based on optical communications at short range, and on acoustic communications at intermediate and long ranges. In particular, we observe that: i) the Sonardyne BlueComm HAL [15] optical modem can provide a bit rate of 5 Mbps within 20 m (supporting the HD Video mode); ii) the FAU Hermes modem [2] can provide ∼87 kbps within slightly more than 100 m (supporting

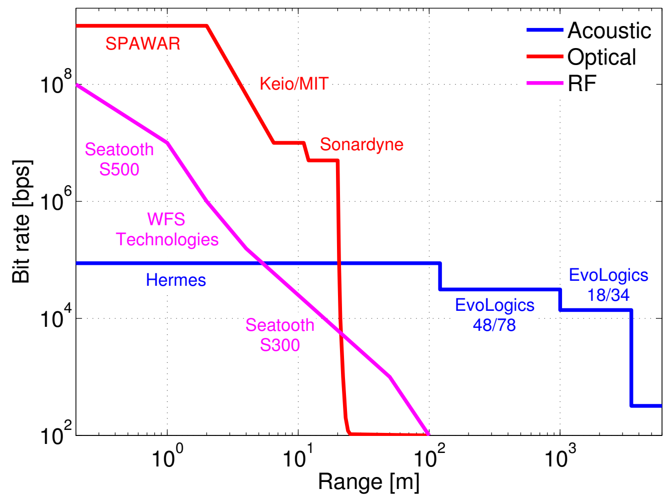

Figure 1. Bit rate vs. range graph obtained by employing the best among the mature technologies listed in Table I. Optical systems offer high bit rates within a range of 20 m, whereas acoustic systems are preferred to achieve longer ranges. RF systems offer consistently lower bit rates at any distance.

mode 2); iii) the EvoLogics S2CR 48/78 modem can provide 31.2 kbps within 1000 m [14] (supporting mode 1); and finally iv) the EvoLogics S2CR 18/34 modem can achieve a bit rate of 13.9 kbps up to 3500 m (supporting mode 0). This is also highlighted in Fig. 1. Finally, we remark that the present technology does not support a smooth transition from mode 2 to mode Video HD through modes 3 and 4. In fact, the bit rate provided by optical systems at short range is already sufficiently large to support mode Video HD, whereas acoustical systems can only support up to mode 2 at larger distances. However, for distances between 20 and 100 m, the development of the signal processing techniques described in [3] may help bridge this gap.[3]

IV. Simulation Results

As a specific example, we will now focus on acoustic communication technologies, and test an acoustic wireless ROV control system using the DESERT Underwater framework [1]. The simulation engine has been modified so that the trajectory of the moving ROV can be controlled at run time based on the reception of messages from the controller. The following subsections introduce the simulation scenario, the details of our model of the Hermes physical layer [2], and the simulation results obtained via a simple CSMA as well as a more efficient TDMA MAC layer.

A. Scenario and parameters

We consider the task of remotely driving the movement of an ROV over a lawnmower-like trajectory spanning a 200 m × 200 m area, where the controller is centrally placed. This leads to a maximum distance of 145 m between the controller and

[3]The energy consumption of communication systems considered above has been neglected in this paper, as it is expectedly lower than required by ROV propulsion. Relevant figures for systems ii)–iv) above are 32 W for Hermes, up to 60 W for the EvoLogics S2CR 48/78, and up to 80 W for the EvoLogics S2CR 18/34. We did not find a specific figure for the Sonardyne BlueComm HAL, although optical modems typically consume limited energy: e.g., [15] reports a 3-Gbyte data transfer using a D-sized Lithium battery.

the ROV, and requires to employ acoustic communications using the Hermes modem. This entitles the system to modes 0 to 2. The bit rate set for the system is the same as the Hermes modem's, i.e., 87.768 kbps. The sound speed is assumed to be constant and equal to 1500 m/s. Command packets sent by the controller have a total size of 1024 bits, whereas the monitoring packets sent by the ROV to the controller have a length equal to L_{mon}, which can be varied depending on the operational mode in order to balance between packet delivery ratio (PDR), efficiency and ROV reporting frequency.

The controller drives the ROV along the desired trajectory by sending absolute movement commands in the form of subsequent waypoints to be covered. In this respect, a key design choice regards the time t_k^{wp} between two subsequent waypoint transmissions. Assuming that the ROV moves at constant speed equal to v, we have $t_{\min,k}^{\mathrm{wp}} \geq \|\mathbf{x}_k - \mathbf{x}_{k+1}\|/v$, where $\mathbf{x}_k$ is the absolute position of the kth waypoint. However, such minimum time gap cannot ensure the correct reception of new waypoints, as a real system also incurs additional delays due, e.g., to queuing, processing and retransmissions. In fact, the latter are a major source of delay and should be explicitly accounted for when choosing the timing of waypoint transmissions. Given that the actual number of retransmissions required for a given waypoint is not known a priori, we choose to set $t_k^{\mathrm{wp}} = t_{\min,k}^{\mathrm{wp}} + t_g$, where t_g is a guard time that can be acted upon to trade off the rate of the movement commands for the probability that the ROV actually received them and had time to act accordingly.

Given the presence of only two nodes, the communication stack set up in DESERT Underwater can be simplified to involve: a PHY layer that reproduces the error rate performance of the Hermes modem as a function of distance (details in Section IV-B); a CSMA or TDMA MAC protocol; static routing; UDP transport; a CBR application layer. The controller is configured to transmit packets at a fixed rate equal to $1/t_k^{\mathrm{wp}}$: this corresponds to assuming that the ROV moves at constant speed (set here to $v = 1$ m/s) and that subsequent waypoints are equally spaced along the desired route. At the ROV side, the application layer is set to transmit monitoring packets (including the information briefly summarized in Section II). Such packets, when appropriate, can piggyback an ACK packet reporting the last waypoint correctly received. Movement commands not correctly received for any reason can be retransmitted until they are preempted by newer commands, which cause the controller to drop older ones.

B. Hermes PHY layer model

We modeled the performance of the Hermes PHY layer by making the following assumptions: i) the transmissions of 12380-bit Hermes frames (corresponding to 9120 information bits + 32 bits of CRC, coded with a $(15, 11, 1)$ BCH code) is subject to the error rate performance reported in [23, Table III], where the probability that a packet is received correctly (or packet delivery ratio, PDR), is considered to be equal to the product of the packet authentication probability (representing the ratio of packets actually recognized as Hermes frames) times the probability that the fraction of erroneous bits in an authenticated frame is less than $1/10$. This is akin to the

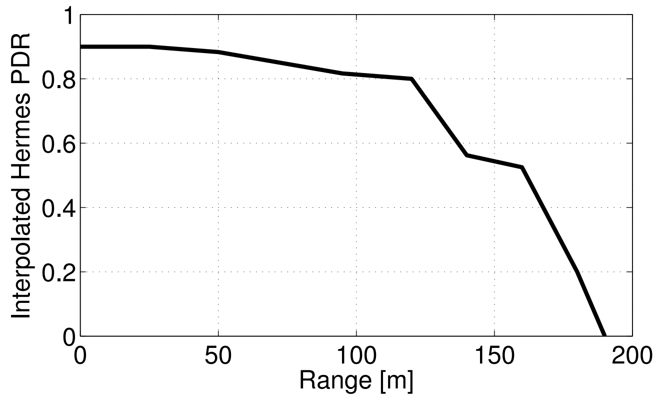

Figure 2. Hermes frame PDR vs. distance between transmitter and receiver as implemented in our Hermes PHY model.

observations in [23]. Linear interpolation is employed between subsequent Hermes PDR samples, and we assume that the PDR drops to 0 at a range of 190 m. The resulting PDR vs. range graph is reported in Fig. 2. These numbers, however, refer to 12380-bit frames, which may not necessarily be the best packet length choice in our setting. To obviate this, we assume that the nodes can transmit any number k of 15-bit chunks, where $m = 832$ chunks form a full Hermes frame, and that the error process is iid across chunks. Under these assumptions, we approximate the PDR of a generic k-chunk packet as $p_c(k) = q_c^{k/m}$, where q_c is the PDR of a full Hermes frame, as shown in Fig. 2.

C. Results—CSMA MAC scheme

We start by considering the case where communications are handled at the MAC layer by means of a simple CSMA MAC protocol. This choice may be suboptimal, but translates into a largely simplified system implementation, as there is no need to enable additional services such as localization or time synchronization between the controller and the ROV. Our main concern at this time is how well the ROV can follow a desired trajectory while at the same time reporting back to the controller in accordance to the operational mode. The desired trajectory for the ROV is depicted using a bold black line in all the following figures. We start from Fig. 3, which refers to mode 0. The top pane shows the desired trajectory superimposed to the simulated ROV trajectory in two cases, $t_g = 2$ s and $t_g = 5$ s. The former enables better responsiveness to the ROV by sending waypoints more frequently; at the same time, it does not leave much room for error control, which may lead to uncompensated packet losses. Conversely, setting $t_g = 5$ s leaves more time to retransmit lost waypoints, at the price of slower ROV responsiveness. The net result is that the deviation from the desired trajectory is acceptably small (almost always lower than 1 m for $t_g = 5$ s, whereas the maximum deviation increases to about 6 m for $t_g = 2$ s. The main reason here is that CSMA transmissions are not coordinated, and packet reception errors may occur due to the deafness of a transmitting node to the reception of packets from its peer.

This same reason leads to even larger deviations if mode 2 is employed. In this case, the amount of information that the

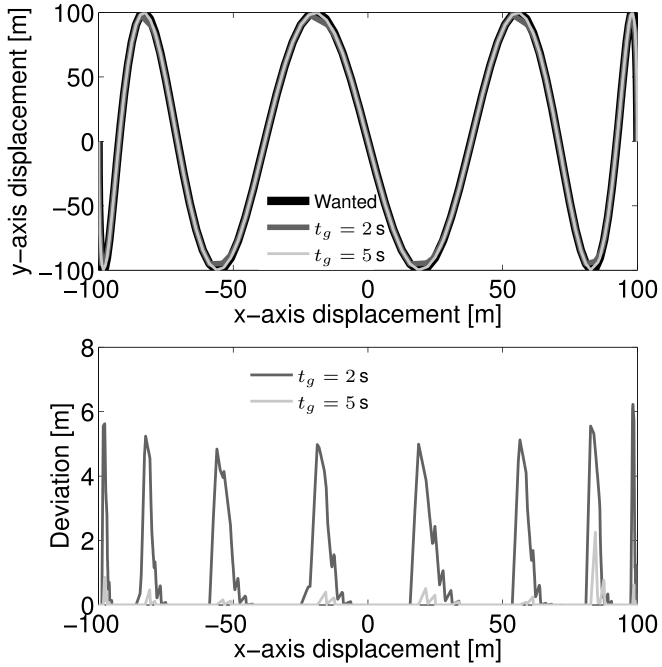

Figure 3. CSMA, mode 0: route followed by the ROV (top) and deviation from the desired route (bottom) as a function of the position of the ROV along the x-axis.

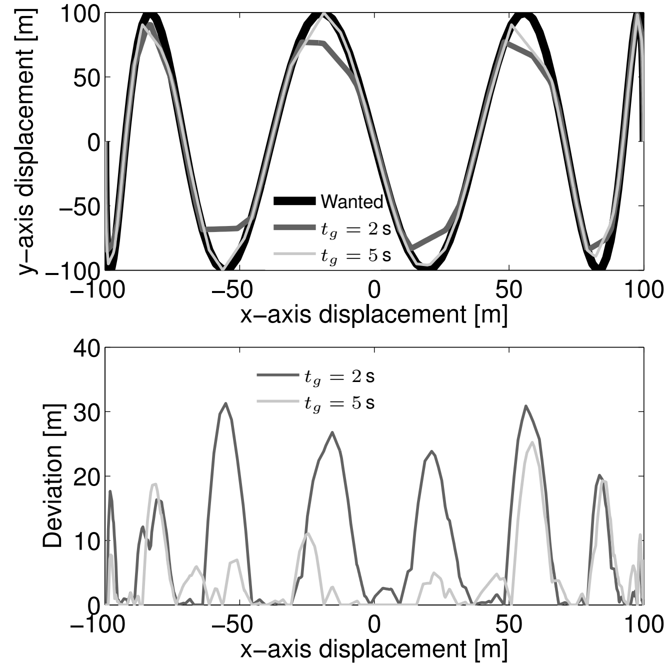

Figure 4. CSMA, mode 2: route followed by the ROV (top) and deviation from the desired route (bottom) as a function of the position of the ROV along the x-axis.

ROV is supposed to transmit is much larger, and the chance that control packets are not heard by the transmitting ROV is much larger than in mode 0. In particular, Fig. 4 shows that even with the larger guard time $t_g = 5$ s between subsequent waypoints, the maximum deviation of the ROV from the desired trajectory in the points farther from the controller is quite significant, typically below 20 m but with one peak around 30 m. With the shorter guard time $t_g = 2$ s, which leaves even less time for retransmissions, 30 m becomes the typical deviation incurred in all portions of the trajectory farthest from the controller. The results motivate the consideration of a deterministic access scheme for channel sharing between the ROV and the controller. In particular, a TDMA scheme will be considered in the following section.

D. Results—TDMA MAC scheme

In this section, we discuss the performance of the ROV control system in the presence of a TDMA MAC layer. We will not perform an explicit simulation of the clock synchronization between the ROV and the controller, but we observe that the continuous transmission of messages from both sides expectedly facilitates the estimation and correction of clock offsets and skews.

The TDMA slot durations $t_{\rm rov}$ and $t_{\rm ctr}$ and the guard interval t_i are set so that both the ROV and the controller have sufficient room to send their packets. While for mode 0 and mode 1 this can be achieved via an equal time division ($t_{\rm rov} = t_{\rm ctr} = 0.6$ s, and $t_{\rm rov} = t_{\rm ctr} = 0.8$ s, respectively), in mode 2 the ROV must send a larger amount of data and needs a larger time share. This has been provided by setting $t_{\rm rov} = 0.8$ s and $t_{\rm ctr} = 4.8$ s. In all modes, $t_i = 0.2$ s.

Fig. 5 reports the performance of the control system in mode 2. We observe that the multiplexing of control messages and ROV data in time improves the performance of the control system considerably. In particular, the ROV no longer has very large deviations from the desired route, and if a guard time $t_g = 5$ s is considered, the ROV never deviates more than 3 m from the expected route. Although the results in Fig. 5 already show promisingly good performance, these results could be further improved by increasing t_g, with the understanding that the operator will have to accept some additional lag when controlling the ROV at points farthest from the controller.

As a final comparison, in Fig. 6 we show the root-mean square error (RMSE) of the actual trajectory followed by the ROV against the desired trajectory. We consider the TDMA MAC scheme and all modes 0 to 2. The curves are plotted against the guard interval t_g, and help set t_g in order to reduce the average trajectory deviation under either operational mode. We observe that the RMSE is lowest in modes 0 and 1, which incur almost the same variation with t_g. In mode 2, the RMSE becomes expectedly higher, although increasing t_g to about 8 s reduces the error down to values comparable with modes 0 and 1. This is in line with the results in Figs. 3–5.

V. CONCLUSIONS

We discussed the feasibility of wireless ROV control in light of the capabilities offered by current optical, RF and acoustic modem technologies. For each technology, we shortlisted available modems that report performance figures measured in the presence of realistic operational conditions, including turbidity, shallow-water channels, and distances on the order of 150 m, which are of interest for the remote control application. We then identified a number of operational modes based on the amount of data to be transferred between the controller and

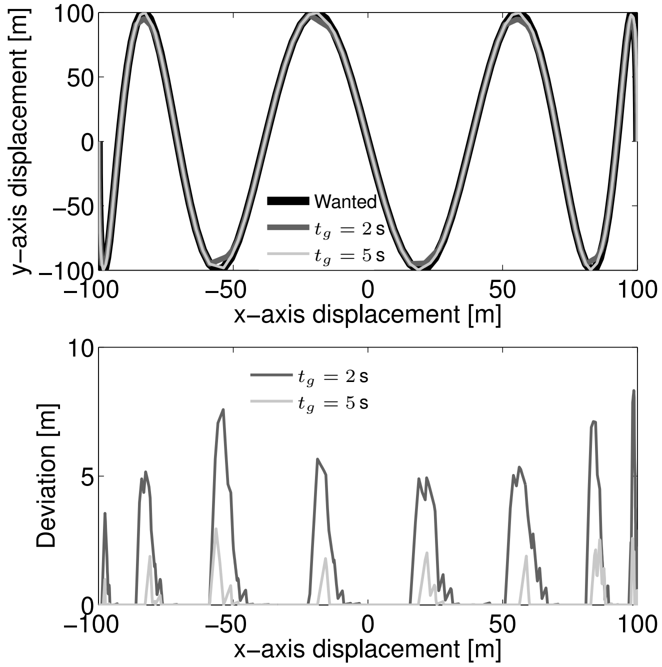

Figure 5. TDMA, mode 2: route followed by the ROV (top) and deviation from the desired route (bottom) as a function of the position of the ROV along the x-axis.

the ROV, and defined the range at which current modems can support each operational mode. One of the main conclusions is that current acoustic and optical technologies outperform RF modems at all distances of interest. We finally focused on acoustic communications and implemented a remote control system in the DESERT Underwater network simulator, which we used to test the capability of an ROV to follow a desired trajectory. In doing so, we compared the CSMA and TDMA approaches for sharing the half-duplex acoustic channel between the ROV and the controller. The results show that TDMA increases the chance that commands and ROV reports are correctly received; in addition, the accuracy of the actual trajectory relative to the desired one can be improved by increasing the guard time between subsequent commands.

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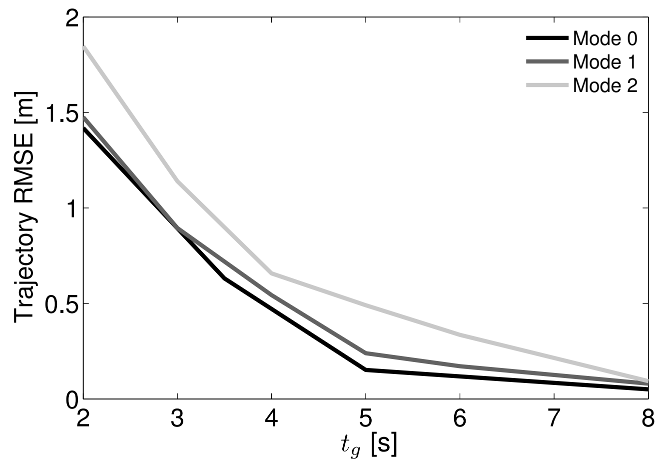

Figure 6. RMSE of the trajectory followed by the ROV as a function of t_g for modes 0, 1 and 2. TDMA is employed at the MAC layer.

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