Linguistic Encryption for Underwater Communication

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***Abstract*—Underwater gliders communicating in an underwater acoustic environment face significant obstacles to implementing secure communications between devices. By adapting a constructed language, we aim to create a secure communication scheme which uses dolphin noises as acoustic signals and simple words as encoded command representations. Security features come from a psuedo-random permutation generator which integrates elements of a stream cipher with an ephemeral key. Our design was validated using experiments on Raspberry Pis in a laboratory setting.**

***Keywords*—Constructed language, Encryption, Underwater Glider, Acoustic Network, RanCode**

I. INTRODUCTION

Underwater gliders have been increasingly used in commercial settings as data collection vessels for their ability to function for long periods of time without human intervention. Yet the low power systems which allow for long-term capabilities significantly constrain feasible approaches to security. Acoustic networks are widely used for underwater devices, but introduce additional obstacles to secure communication. We draw a parallel between device acoustic networks and the communication systems of underwater mammals; in particular, dolphins use a wide variety of noises to communicate underwater between individuals. We believe that dolphin noises can form a basis for acoustic signals between devices.

We model messages between gliders as simple directional instructions and basic commands which must be conveyed precisely. Toki Pona is considered the smallest functional constructed language with enough flexibility for a full range of semantic content. We use Toki Pona to encode messages for transmission between gliders at the needed level of specificity including any control algorithm created by humans. To provide security, we combine these encodings with a deterministic permutation generator known as RanCode [1]. Using an identical ephemeral initial seed in each device, we can ensure that all encoding permutations will match across devices.

II. BACKGROUND

A. Prior Work in Underwater Communication

Underwater communication systems are significantly limited by the constraints of their environment. Transmissions are impeded by constantly shifting conditions, slower propagation times, multi-path interference, and other obstacles which make traditional land-based protocols infeasible [2]. Systems typically use radio frequencies, optical transmission, or acoustic signals to communicate between devices [3]. Optical methods can be used within direct line of sight (e.g., 10 or even up to 150 meters) to communicate at a high data rate, but lose effectiveness at larger distances [4]. Radio frequencies are sometimes used, but have high attenuation rates leading to a very short effective range [5]. The bulky equipment is often prohibitively expensive for even moderate results [6]. By far the most widely used method is acoustic networks [3], which provide the longest range (1+ km) and most reliable data transmission for low power systems [4]. However, acoustic networks suffer from variable delays and low bandwidth due to sound refracting underwater, multi-path interference, Doppler spread, and more [7]. In recent years as underwater devices have become more popular, there has been an increased need for interoperability. JANUS is the only available open standard for these communications to date but it does not include security in the original specification [8].

B. Prior Work in Underwater Encryption

In recent years as underwater unmanned autonomous vehicles (UUAVs) have become more popular in commercial and military applications, interest in developing security measures for underwater networks has dramatically increased. Acoustic networks are subject to security vulnerabilities such as eavesdropping, jamming, spoofing, and more [9] [10]. Countermeasures have been proposed for these attacks in multiple configurations using a variety of approaches including game theory [11] and machine learning [12]. Many of these approaches do not fulfill all requirements of secure communication at once [5] and must sacrifice security due to power constraints [10].

While symmetric key and public-key infrastructure remains the most popular for securing typical radio networks, they require significant overhead which makes them infeasible for underwater devices [13]. Modern acoustic networks use a variety of tactics to secure communication which can generally be characterized as either traditional cryptography or physical layer security [5]. The power constraints of underwater devices have motivated interest in physical layer security over traditional methods [14] [15]. Many of these schemes remain largely untested within the available literature on mobile underwater devices [16]. Our approach addresses a key need in the field by providing a solution for sending commands between underwater devices which maintains a high degree of security over a low-power system. To the best of the writers' knowledge, this paper is the first publication to propose communication in a constructed language using animal noises as a basis for acoustic network signals.

C. Toki Pona

There is a small but passionate online community centered on constructed languages, or conlangs. Perhaps the most well-known example of a conlang is Esperanto, developed by L. L. Zamenhof with the goal of creating an international second language [17]. Today, many linguists including those with less formal training experiment with combining a set of grammatical properties with an invented vocabulary in the hopes of creating a usable language.

Widely recognized as the smallest functional constructed language, Toki Pona was created by the linguist Sonia Lang in 2001 with a focus on minimalism [18]. There is abundant documentation on the linguistic structure, vocabulary, and teaching of the language, as well as an online community dedicated to translating works from other languages [19]. The entire language consists of 120-140 morphemes, with most words being one or two syllables for about 95 syllables total [20]. There are 14 total phonemes, consisting of nine consonants and five vowels (as shown in Table I) [21]. As with many small conlangs, it is necessary to group basic morphemes together to "build up" to more complicated ideas [19] [22]. Relying on additional context, proponents claim it is possible to communicate with the extensiveness of a natural language [22]. There has been promising exploration into the use of Toki Pona for artificial intelligence and other alternative communication systems [23] [24]. We believe Toki Pona can implement any set of commands based on human language; therefore, the approach described in this paper should be scalable to any control algorithm designed for underwater gliders.

TABLE I
TOKI PONA ALPHABET

Consonants	j, k, l, m, n, p, s, t, w
Vowels	a, e, i, o, u

D. Autonomous Underwater Vehicles

Underwater unmanned autonomous vehicles (UUAVs) are devices used in wide-reaching applications in underwater environments including commercial, research, and military usage [25]. They can remain deployed for long periods of time with little human intervention, ideal for data collection studies and field surveys. UUAVs are most often torpedo-shaped but can also include hydrodynamics-focused or biomimetic designs. We specifically focus on underwater gliders, UUAVs characterized by a pair of wings which allow for motion via buoyancy-based propulsion [26]. This low power mechanism makes gliders favorable for missions over large distances [27]. Some of the most common underwater gliders are the Seaexplorer glider, the Slocum glider, and the Seaglider, each of which have lifespans of thousands of hours [26] [28].

Due to their role as data collection devices, UUAVs are often equipped with a variety of sensors [29] [27]. They also may have configurable control architectures designed to communicate with large vessels or with stationary transmission nodes [2] [30]. Despite their increasing usage in fields such as commercial surveying, the authors of this paper were unsuccessful in finding prior published work specific to protecting these communications from adversaries or how interested parties could interfere with UUAV networks, other than the more general work in acoustic sensor networks cited earlier in Section II.B.

E. Underwater Communication by Animals

Underwater mammals such as dolphins and whales are known to have extremely complicated communication systems and use a series of noises including whistles, clicks, and pulses to convey information amongst themselves. There are between 12 and 25 distinct naturally occurring dolphin noises [31]. These sounds can also be modulated, although they might strictly still be considered the same kind of sound. This allows for an additional degree of flexibility in creating even more perceptually distinct units. Each noise lasts around 300 milliseconds and can be heard at a distance of up to 20 kilometers through the water [32] [33]. Dolphins are thought to convey complex semantic and syntactic information [34], as well as pair objects and sounds together even when not present with the described object [33]. Along similar lines, dolphins have been known to assign themselves signature whistles used as names; individual dolphins respond to only their own whistle [35]. In a manner analogous to human conversations, dolphins have a tendency to wait and listen to one another before responding with seemingly connected information [33]. There is evidence that dolphins create more new whistles in the presence of humans, perhaps as a means of communicating [36].

F. RanCode Permutation Generation

RanCode is a pseudorandom permutation generator designed in VHDL with low computational overhead, published in MECO 2021 [1]. It creates random encodings, four bits at a time, within one clock cycle and without saving a copy of data in memory. An ephemeral key is used to produce permutations generated by Knuth shuffle units [1]. After every permutation generation, the key is hashed and updated by SHA-3. Crucially, RanCode is deterministic, meaning that any two devices with the same seed value and inputs will have the same output after the same number of iterations. The assurance that each input will correspond to a unique, but identical, output provides the basis for decoding across multiple devices. When this key is correctly produced and used by two communicating parties, either one can properly understand messages from the other using their independent module.

RanCode adopts characteristics of a stream cipher in that individual elements are passed in continuously. Each piece of data is manipulated to create a ciphertext using a cryptographic key, which in this case is the initial input (seed) and subsequent SHA-3-based outputs [1]. This approach offers a very high level of security as SHA-3 is a one-way function.

III. SCENARIO

The scenario that is the basis of the work presented in this paper is shown in Figure 1. As depicted in the figure, a team of underwater gliders searches throughout a very large underwater domain, perhaps even as large as an ocean. This team has one glider that is labeled as the Leader and is responsible for making real-time decisions for the team that ensure both safety and efficiency of the search. The rest of the gliders are labeled as Followers as they respond to the instructions and commands communicated by the Leader. We assume that the team of gliders is able to convene in a secure location before the search to understand their search plan.

The Leader communicates real-time commands to the other gliders that can lead them to their search location and direct them throughout their search. The Followers need to communicate back to the Leader during emergency situations or to update any progress they make during the search.

An important aspect of our scenario is the confidentiality of all glider communication occurring throughout the search. The gliders need to transmit encrypted commands that any adversary will be incapable of understanding. This adversary could be another team of gliders or anyone who has the ability to hear the commands being transmitted between gliders underwater.

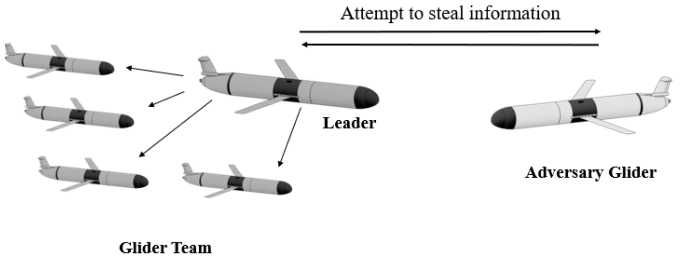


Fig. 1. Glider Communication

An example scenario of our research is the search that occurred after Titan, a submersible designed by OceanGate, went missing and ceased communication in June 2023 [37]. The incident led to several search teams being sent out to locate the submersible and uncover what had occurred. These teams had reasons for not wanting their information to be available to each other or the public, including legal concerns, that reflects our scenario.

IV. DOLPHIN ACOUSTIC SIGNALS

We specifically choose to use dolphin noises over other forms of animal communication due to the variety of and short duration of noises available, the potential to convey semantic content, and the ability for the sound to carry over kilometers. While whales display similarly complicated communication systems, the structure of their songs are not conducive to short messages [38]. In comparison, the short, discrete chirps, whistles, and pulses made by dolphins mostly last for approximately 300 milliseconds each and can each individually carry semantic meaning [35]. Commands are typically in the 20kHz frequency band, well within the range of human hearing [33]. This is an analogous structure to human communication, making it ideal for encoding commands.

V. LINGUISTIC METHODOLOGY

We propose adapting Toki Pona into a basis for encrypting messages as they are sent underwater. The language will be adapted when possible to shorten the length of translations, allowing messages to be transmitted between gliders faster. The language originally has 14 characters (see Table I) and we use an additional dummy character for padding purposes and to represent spaces, choosing the character ‘d’. Because Toki Pona has a limited number of phonemes while maintaining the complexity of a full language, theoretically any communication can be uniquely encoded despite the low-power network restrictions.

TABLE II
SCENARIO COMMANDS, TOKI PONA, TWO-CHARACTER MAPPING

Command	Toki Pona	Mapping	Padding
North	sewi	aa	aa dd
Northeast	suno sewi	ae aa	ae aa
East	suno open	ae ai	ae ai
Southeast	suno anpa	ae ao	ae ao
South	anpa	ao	ao dd
Southwest	anpa suno	ae au	ae au
West	suno pini	au	au dd
Northwest	sewi suno	am	am dd
Stop	pini	au	au dd
Watch	lukin	am	am dd
Forward **	sinpin **	ak **	ak **
Backward **	monsi **	al **	al **

To showcase our scenario in a small example, we have implemented a set of 12 commands shown in Table II. As a proof-of-concept small scale example, the command set allows for 2-dimensional exploration. Table II shows each command first in English and then in Toki Pona (adapted to be short). As each dolphin sound requires approximately 300ms, we map the Toki Pona words to two characters each, e.g., the command North in English become sewi in Toka Pona which is then coded as ‘aa’ resulting in half of the length (sewi has four characters). In order to have a uniform length for all commands in our showcase scenario, the last column of Table II uses the letter ‘d’ as padding; the padding is stripped away when translating commands. Please note that if commands have different lengths, security would be reduced as an eavesdropper could infer information from command length.

The final two commands in Table II, Forward and Backward, have a placeholder of ** which can input a 2 digit number of predefined units to specify the distance gliders should travel. The digits are mapped to characters as well; Table III depicts these mappings.

Overall, Table II shows a small sampling of possible commands to allow for the gliders to perform a search and be guided by the leader.

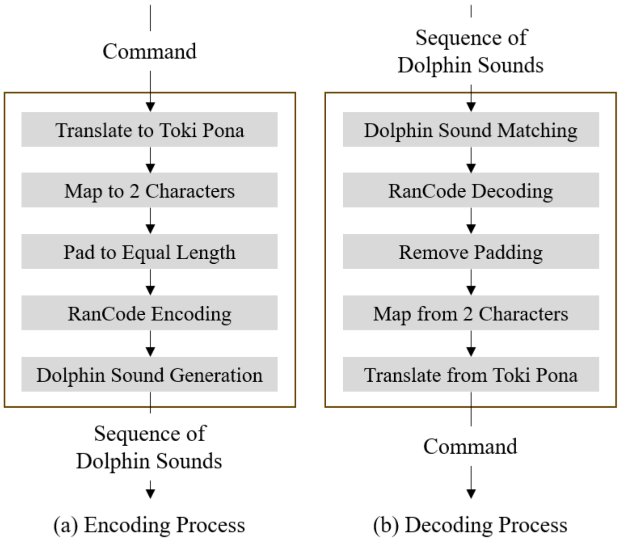
TABLE III
DIGIT MAPPINGS

Digit	0	1	2	3	4	5	6	7	8	9
Toki Pona Mapping	a	e	i	j	k	l	m	n	o	p

Our implementation uses the following steps:

1) Translate the desired command into our adaptation of Toki Pona.
2) Map each Toka Pona word to a two-character representation.
3) Apply padding to prevent length-based attacks.
4) Run RanCode to create a new encoding scheme specific to the message.
5) Express the message as a sequence of dolphin sounds mapped to each of the Toki Pona phonemes.

Figure 2(a) depicts the aforementioned steps. Figure 2(b) shows the decoding process, which reverses the steps that messages undergo when being encoded.



(a) Encoding Process (b) Decoding Process

Fig. 2. Communication Program Architecture

Command representations in Toki Pona draw on the inherent properties of the language to communicate clearly and concisely. Drawing upon the straightforward nature of the messages, all conjunctions are removed. Semantic significance is instead placed on the location of each word in the phrase to indicate cardinal direction. For example, the Toki Pona *suno sewi* (English gloss “up and sun start”) becomes Northeast, while sewi suno (English gloss “up and sun end”) becomes Northwest. We also forgo Toki Pona’s number system because it is similar to Roman numerals and takes a large number of characters to represent a single number. Instead, we have replaced Toki Pona’s number system with our own where digits are mapped to characters as shown in Table III.

Due to Toki Pona’s small vocabulary (approximately 120 to 140 words), it is possible to map each word to a unique permutation of two characters from the Toki Pona alphabet (note that $14^2 = 196$ which is greater than 140). We employ this mapping technique to the Toki Pona message in order to shorten the length of the message, allowing more data to be sent in a shorter amount of time between the gliders.

Once all messages have undergone the first four steps shown in Figure 2(a), each character will be mapped to a dolphin sound. Gliders will transmit messages as sequences of dolphin sounds that allow for underwater. acoustic communication. Our overall goal is that sets of dolphin sounds representing individual characters will be transmitted through the water and understood by the other gliders but appear random to an adversary.

VI. ENCRYPTION METHODOLOGY

A RanCode module is used to create encodings for each message. The module encodes one character at a time using permutations of a character list created by a Knuth Shuffle. In order to acheive a power of two (2^4), a character list of length 16 is used to apply our scenario. The character list contains all 14 characters used in Toki Pona and two additional characters. Those additional characters are ‘d’ which is used to pad the length of all messages and another character that is used in encryption mappings. The module will use an ephemeral key that self-updates by hashing its previous value using SHA-3. Each key will be used once to create a look up table that will encode or decode a single character. Therefore, every character will be encoded individually using look up tables that were created from different inputs.

The RanCode module aims to allow for pseudorandom encodings that will not be able to be predicted by an adversary. All gliders are given the same seed that will allow them to all begin their modules at the same encoding. As SHA-3 updates the keys in each glider, the systems in each glider maintain synchronization as they perform the same number of operations in order to communicate in our adapted Toki Pona language.

VII. EXPERIMENTAL METHODOLOGY AND RESULTS

We have conducted an experiment that tests the linguistic and encryption methodology of our proposed implementation. The experiment is conducted on four Raspberry Pis that run independently. The Raspberry Pis exclusively interact through a server chatroom that runs on Raspberry Pi 1 [39]. This chatroom allows for messages to be broadcast from one Leader Raspberry Pi to the others. One of the Raspberry Pis acts as the Leader, sending encoded commands from our scenario command list. The other three Raspberry Pis individually decode and interpret each command. This behavior is outlined in Figure 3.

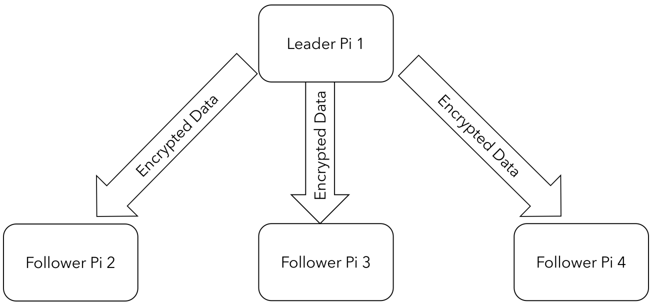


Fig. 3. System Architecture

A. Experimental Setup

Our experiment is conducted on 4 Raspberry Pis (Version 3 Model B and Version 4 Model B) that run Raspberry Pi OS. Each Raspberry Pi has an 8GB microSD card and utilizes Wi-Fi communication. The setup is shown in Figure 4.

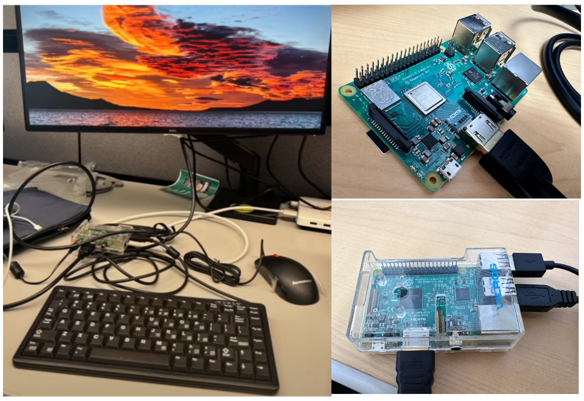


Fig. 4. Raspberry Pi Setup

B. Experimental Flow

The flow of our experiment is as follows:

1) Leader Pi 1 runs a server script [39], opening a chatroom that all Raspberry Pis connect to and communicate through. The other three Raspberry Pis connect to the chatroom opened by Leader 1.
2) Leader Pi 1 begins running `leader.py` while Follower Pis 2, 3, and 4 begin running `follower.py`, assigning their respective roles as one leader and three followers.
3) A list of plain text commands are entered into Leader Pi 1 which undergo the encoding process on each command before broadcasting the encoded commands to the established chatroom. Figure 3 illustrates the architecture followed.
4) Follower Pis 2, 3, and 4, independently, read each encoded command from the chatroom and display the decoded version [39].

C. Experimental Results

Leader Pi 1, acting as a leader, is able to successfully encode commands following our linguistic and encryption methodology. Follower Pis 2, 3, and 4 are all three able to successfully decode and interpret all commands entered into the chatroom by Leader Pi 1.

Table IV depicts a small subset of our experiments and shows the process of communication from Leader Pi 1 to the chatroom to Follower Pis 2, 3, and 4. We are able to see both the original and encoded version of each command as well as see that all of our Follower Raspberry Pis are able to successfully understand the transmitted commands. Note in Table IV that the second time the Leader Command is "South," the message broadcast by the Leader Command in Toki Pona characters has no relationship to the first time due to randomization provided by RanCode. Our experiment was not conducted under water and hence the Toki Pona characters were transmitted as such without translation to dolphin sounds.

TABLE IV
COMMAND COMMUNICATION

Leader Cmd	Broadcast	Pi 2 Display	Pi 3 Display	Pi 4 Display
South	mpas	South	South	South
Forward 45	axom	Forward 45	Forward 45	Forward 45
Northwest	tjjd	Northwest	Northwest	Northwest
South	eidu	South	South	South
Stop	ssaw	Stop	Stop	Stop
Watch	sddu	Watch	Watch	Watch

VIII. PRACTICAL EXTENSIONS

We believe that the research presented in this paper can be extended with a Global Positioning System (GPS) and quaternion-based directions to locate and control movements of the gliders, extending our two-dimensional proof-of-concept experiment to three-dimensional search scenarios [40]. By including GPS, an algorithm can be developed that optimizes commands for the glider to move between coordinates and ultimately to the destination point to ensure the best possible efficiency.

There are several advantages to implementing quaternion-based glider movements. One advantage is the elimination of singularities and edge cases that can occur in Euler angle rotations where two rotational axes are aligned, leading to one less degree of freedom [41]. However, with quaternion arithmetic, the four-dimensional system ensures that all orientations are unique and therefore allows the gliders to have a more reliable and precise tracking and movement system [42].

IX. CONCLUSION

The proof of concept presented in this paper utilizes a modified version of Toki Pona and acoustic transmission of dolphin sounds to represent the first secure communication technique for underwater gliders performing a two-dimensional search. The use of RanCode protects messages from being understandable by an adversary. We saw that four Raspberry Pi systems were able to communicate and interpret encoded search commands that underwent the first four steps of our encoding process. The final step of the process outlined in Figure 2, Dolphin Sound Generation, will need to be tested in future studies to verify the ability to transmit messages acoustically underwater. We have shown possible enhancements to enable three-dimensional search, which will need future studies to be conducted to confirm. We believe this paper to be the first to propose encrypted underwater communications between gliders based on dolphin sounds.

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