Abstract— Swarms of robots in heterogeneous environments working together in a System of Systems, raise the need for suitable inter-swarm communication. This paper presents a potentially viable solution. Communication was found to be successful through ZigBee Radio Modems in physical experiments that were conducted. An extensible standards based protocol to accommodate different types of data was developed for use among the swarm robots. This communication system allows for dynamic swarm expansion, where new members can be added to the swarm family. This enables coordination among robots within and between swarms in a system of systems framework.

Index Terms— Systems of Systems, Underwater Communication, Surface communication, Swarm Robotics

I. INTRODUCTION

The Autonomous Control Engineering (ACE) lab of The University of Texas at San Antonio is working towards a System of Systems of Robotic Swarms with cooperation among swarms in air, land, and sea [1], [2]. Robotic swarms could be used as part of a System of Systems for applications such as augmentation of an environmental research knowledge base [3], sensor network type application [4], military, security, aerospace and disaster management.

The concept of SoS is essential to effectively implement and analyze large, complex, independent, and heterogeneous systems working (or made to work) cooperatively. The main thrust behind the desire to view the systems as an SoS is to obtain higher capabilities and performance than would be possible with a traditional system view. The SoS concept presents a high-level viewpoint and explains the interactions between each of the independent systems. However, the SoS concept is still at its developing stages. Based on the literature survey on system of systems, there are several definitions.

Detailed literature survey and discussions on these definitions are given in [5]. All of the definitions of SoS have their own merits, depending on their application. Our favorite definition is “Systems of systems are large-scale concurrent and distributed systems that are comprised of complex systems.” The Fig. 1. Depicts the main characteristics of SoS.

Fig. 1 Systems of Systems main Characteristics [6]

The interoperability in complex systems (i.e. multi-agent systems) is very important as the agents operate autonomously and interoperate with other agents (or non-agent entities) to take better actions. Interoperability requires successful communication among the systems. Thus, the systems should carry out their tasks autonomously as well as communicate with other systems in the SoS in order to take better actions.
for the overall benefits of the SoS, not just for themselves. The Integration implies that each system can communicate and interact (control) with the SoS regardless of their hardware and software characteristics. This means that they need to have the ability to communicate with the SoS or a part of the SoS without compatibility issues such as operating systems, communication hardware, and so on. For this purpose, an SoS needs a common language its components can speak. Without having a common language, the SoS components cannot be fully functional and the SoS cannot be adaptive in the sense that new components cannot be integrated to the SoS without major effort. Integration should also consider meaningful control aspects of the SoS. For example, a system within an SoS should be able to understand commands and/or control signals from other SoS components [6].

In order to achieve some of the main characteristics of system of systems approach, communications play a vital role. This paper investigates a means of extending the protocol for communicating among heterogeneous interoperable systems as depicted in Fig. 2. In our case land, water and air are three different heterogeneous systems to be taken into consideration. The next section briefly reviews underwater communication among autonomous underwater vehicles. Section III is about communication between surface and underwater vehicles. Section IV is about communication between unmanned air vehicles and ground.

II. UNDERWATER COMMUNICATION

Autonomous underwater vehicles (AUVs) are unmanned, untethered, self-propelled platforms. AUVs have the potential to revolutionize our access to the oceans and to address the critical problems faced by the marine community such as underwater search/rescue, mapping, climate change assessment, underwater inspection, marine habitat monitoring, shallow water mine counter measures and scientific studies in deep ocean areas. Localization, navigation, and communication are three primary requirements for AUVs. In getting AUVs to solve problems comprehensively, a key issue is communication. Underwater communication can be implemented in numerous ways including acoustic propagation, fiber-optic communication, and radio modems. Acoustic propagation faces a lot of problems compared to radio modems. These problems are mainly due to very limited bandwidth, large signal propagation time and overload on the receiving antenna by local transmit power levels (Near and Far problem). The limited bandwidth implies that the use of multi-channels techniques is very limited. The near and far problem occurs when an acoustic unit may not transmit and receive at the same time because of local transmit power levels. Large propagation delays involved in acoustic propagation are in the range of seconds. All these factors lead to choosing some alternative technology to communicate effectively between the AUVs. Researchers have attempted to address these issues. A few have tried to use fiber-optic cables to implement underwater communication, which proved to be expensive, requiring high maintenance and were prone to fiber-optic cable damage. Looking in to all these factors we considered radio modems for communication [7].

The radio modems chosen are Zigbee modules. Zigbee is a low-power wireless communication technology and an international standard protocol for the next-generation wireless networking. It reduces the data size and allows for lower-cost network construction with simplified protocol and limited functionality. Zigbee uses the MAC layers and PHY layers defined by IEEE® 802.15.4, which is the shortest-distance wireless communication standard for 2.4GHz [8]. The benefits of Zigbee are that it supports three different topologies: star, mesh, cluster-tree networks, robustness, simplicity, low-power consumption and mesh networking. 802.15.4 provides a robust foundation for Zigbee, ensuring a reliable solution in noisy environments. Finally, multiple levels of security ensure that the network and data remain intact and secure [9].
The problem, however, with underwater communications using radio is radio doesn’t work very well, if at all, underwater. To achieve a distributed protocol network for underwater communication, we need to find out the range of each module in underwater. So the following experiments are conducted. We tested our Zigbee modules in a 9 foot deep swimming pool to examine the affect of attenuation on range between transmitter (base) and receiver (remote). Also depth of base and remote were considered. For every combination of range and depth, received signal strength (RSS) and data packet success rate were recorded. Each time 15 packets of information is sent from base to the remote. Base, remote and the experimental setup is shown in Fig. 3.

From this experiment, the received signal strength is obtained at different depths and different distances between base and remote. Observing the received signal strengths at different levels at certain stage, we can approximate the distance between the modules. This approximation helps us to find out the approximate distance between AUVs and acts as a secondary localization system. Results of the experiment are shown in Fig. 4. From Fig. 4 we can infer that received signal strength decreases as the depth and distance between base and remote increases.

From above experiment we know the range of radio modem underwater. Next issue to be discussed is how to communicate between these radio modems underwater to achieve effective communication among the small fleet of AUVs to solve a problem cooperatively.

In the proposed approach we assume the position of each AUV is known by existing localization techniques [10]. The position of robot is given in the form of (X-axis, Y-axis, and Z-axis). Consider the scenario in Fig. 5. In this case we consider these small circles representing nodes that are present in AUVs. We need to communicate among AUVs. A node should send some information to G node to establish communication. In this approach position of the robot is also included with the acknowledgment. Every node has also a unique identification number, and every packet has unique identification number corresponding to its destination (In this case the packet identification number is destination G identification number). Each time a node receives a packet, it first verifies that its identification number matches the packet identification number. If so it stores the packet in the memory and in turn broadcasts an acknowledgement, else transmits the packet to neighboring nodes. In the proposed approach master can be switched in case of failure in the system (in this case A is the master node).

**Algorithm for proposed Approach**

1) Determine the position of all the existing nodes using the broadcasting method. In broadcasting method the master node send packets to all other the nodes. It receives back the acknowledgment from other nodes with their respective positions.

2) The shortest paths are calculated between the master node and destination node. The shortest paths refer to that with the fewer hops from the master node to the destination node.

3) If there are two or more shortest paths, the most reliable path is chosen from the shortest paths.

4) Reliable path is calculated based on the physical distances between the nodes.

5) Select the largest physical hop distance from each shortest path. The largest physical hop is calculated using the following distance formula.
Distance Formula is \[ \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2 + (z_a - z_b)^2} \]

6) When comparing the largest hops from each shortest path, the smallest of largest hop is chosen.

7) Reliable path is decided based on the result of step 6.

8) Each time a node acknowledges to master node it also updates its position. Based on this, the master node verifies if there is any change in the position of the nodes.

9) If there is any change in the position of nodes, go to step 1.

10) If there is no change in the position of the nodes use the existing path to send all the packets.

Finally, the packet reaches destination node G. This approach requires at least 4 hops to receive a packet from source (A) to destination (G). As the number of hops decrease, the time delay and power consumption also decrease. The proposed approach achieves effectiveness in communication between autonomous underwater vehicles.

III. UNDERWATER TO SURFACE COMMUNICATION

In this section our aim is to establish communication connectivity between underwater and surface vehicles. Wire-line communications could be established with all submarines, but the restrictions on mobility such as entanglement suggest wireless communications should be accommodated at some point, whether at the end of a wire, or from a communication device at the surface. Once communication is made to the surface, a surface vessel could relay signals to other swarms outside of the water. Wireless communications includes sonar, laser, and radio frequency. Laser suffers from being difficult to point, as the Underwater Autonomous Vehicles (UAVs) need to locate one another, and even then murky water could be a common problem. Sonar travels well underwater, but the signal travels slowly with low bandwidth. High end commercial underwater sonar modems are limited to 9600 baud. A low cost alternative may be radio communications. The main disadvantage of radio communications is that it suffers from heavy attenuation underwater due to the skin depth associated with impure water’s conductivity. Skin depth measures the distance a radio signal can travel through a medium before attenuating to \( e^{-1} \) of the original signal power, and is calculated by:

\[
\frac{\omega}{\mu} \sqrt{\frac{\mu_0}{\varepsilon}} \left( \frac{\varepsilon}{\varepsilon_0} \right)^{\frac{1}{2}} - 1
\]

Where \( \omega \) is the frequency, \( \mu \) is the permeability of the water, \( \varepsilon \) is the permittivity, \( \sigma \) is the electrical conductivity.

The ACE lab has been using XBee Pro modules for communications among land based vehicles, and is experimenting with using these modules for communications between underwater vehicles and surface vehicles. Experiment pool type, methodology, Observations are mentioned in [11].

Vertical transmission was performed in a saltwater pool using various antennas with the results shown in Fig. 6. All three antennas gave surprisingly steady results for increasing depth up to the bottom of the pool, where the omnidirectional antenna signal dropped off. The Yagi antenna performed...
worse than expected at all depths compared to the omnidirectional antenna. The parabolic antenna performed better than the omnidirectional antenna, as expected, but the next measurement measuring signal strength for misaligned antennas gave counterintuitive results. The results in Fig. 7 shows that the direction the parabola was pointing did not have the expected strong effect on the signal strength.

We have demonstrated viability of underwater to surface communications by using underwater radio communication. This exercise has demonstrated underwater to surface communication as a proof of concept for a communication among heterogeneous interoperable systems involving air, land, and sea-based swarms of robots.

![Fig. 8 The effect of misalignment on a parabolic antenna reception](image)

**IV. AIR TO GROUND COMMUNICATION**

In order to interact between these two physical domains, it is needed to create a viable communication system with a common protocol that can be used on various platforms. The communication protocol must allow a dynamically expandable swarm, where additional robots can be added easily during a real-time application. Additionally, the protocol must also be flexible enough to accommodate different types of data such as image, video, GPS locations, control messages etc. Exact requirements of data types in the communication protocol can vary depending upon the swarm mission. Such requirements of a communication protocol for a swarm level mission can be determined from the following scenarios. Fig. 9 depict a swarm of various robotic platforms collaborating in air and ground domains for a multi-domain system.

Electronic communication can be implemented in wire-line and wireless configurations. Practical limitations of mobility restrict the extent to which wire-line communication can be used. Wireless communication can be achieved in many ways including acoustic propagation and radio-frequency (RF) communication etc. Systems utilizing acoustic propagation as a means of communication face many drawbacks. All these limiting factors lead us to choose RF technology to provide a solution for our swarm communication system.

![Fig. 9 Scenario of interaction between two physical domains](image)

In our case, we use 2.4 GHz XBee-PRO 802.15.4 as radio modem. XBee-PRO 802.15.4 modules, developed by Maxstream Co, are low-cost, low-power consumption, radio-frequency modems for communication system. To operate on this frequency band which is a standard to different types of devices, the XBee-Pro radio modem uses a set of protocols called ZigBee. ZigBee is a low-power wireless communication technology and an international standard protocol for the next-generation wireless networking. ZigBee uses the MAC layers and PHY layers defined by IEEE® 802.15.4[8], which is the shortest-distance wireless communication standard for 2.4GHz. IEEE® 802.15.4 provides a robust foundation for ZigBee, ensuring a reliable solution to noisy environments. Features such as channel assessment and channel selection help the device to pick the best possible channel, avoiding other wireless networks such as Wi-Fi. Ability to perform routing is one key feature that helps ZigBee differentiate itself from other low-cost technologies. ZigBee based networks also allow customized topology and protocols

**Protocol Design:**

ZigBee based radio modems provide the PHY and MAC layers for a communication protocol. It allows the freedom of using a custom protocol for the swarm of robotics. Serial Line Internet Protocol (SLIP) provides us the benefits of low overhead requirements and a simple base to create a customized protocol to fit the needs of the swarm [12]. SLIP requires the use of a special character set for a control method: “flag”, “end”, “escape”, “modified flag”, “modified end”, and “modified escape”. Messages transmitted using SLIP will begin with a 1-byte flag character and end with a 1-byte “end” character. When the transmitted data matches the characters used in the special character set, the data is replaced with an escape character followed by a “modified” version of the original byte. Any array of commands could also be sent in the SLIP protocol which does not require any knowledge of data size. This allows the transmission of extensible messages. This will greatly reduce the need for
standardization in order of specific bytes in both the transmitted and received packets. Many other protocols specify source and address fields in the header of a transmitted message. Addressing and routing can be handled in this source/destination format by including both domain and swarm type identifier in the transmitted message data. Swarm masters can check a received message for the domain and then the swarm identifier to determine if the message is for their swarm or not. Slave members of a swarm could check for the swarm identifier and a specific robot identifier to understand whether the message is for them or not. If the message lacks a specific robot identifier, then the message is being sent to the master of its ground swarm. If messages are to be broadcasted to all members of all swarms, then a broadcast type identifier will override the necessity of a source and address field.

One major limitation not addressed by the SLIP protocol is error correction. The simplest form of error correction is a simple checksum. Simple checksums have the ability to be able to detect either one or two bit errors. A more robust approach involves a cyclic redundancy check (CRC). A CRC is more robust than a simple checksum because it has the ability to check multiple bit errors. A major drawback to using a CRC is that the computational time is greater than that for a simple checksum; however the benefit of checking multiple bit errors when they occur is much greater than the cost of computation time for our robotic swarm. There are many different CRC checksum standards that exist for different levels of error checking, correction and data sizes. The specific CRC that we have considered in this work is a CRC-CCIT which has a divisor polynomial of $x^{16} + x^{12} + x^5 + 1$. This can be implemented by processing one byte at a time and adding 2 bytes of overhead to a transmitted message. Low overhead, robust error checking and an option for an extensible message data allow for a simple, expandable protocol that can be used on various platforms.

V. AIR TO SURFACE COMMUNICATION

Similarly like air to ground communication, air to surface communications can be achieved. These surface vechiles can relay messages to underwater vechiles and form a Systems of Systems Communication for heterogeneous independent operable systems.

III. CONCLUSION

ACE center is focusing on developing systems of robotic systems technology for heterogeneous environments. We have demonstrated significant progress in communication technology towards that goal. To accomplish this, we physically tested low-cost wireless communications in diverse environments and mediums including underwater. Having established that low-cost wireless communication can be accomplished in these environments, we have devised protocols for communication among robots within swarms and between heterogeneous swarms. This communication technology has been designed to be extensible with intent of application in net-centric systems of systems to benefit mankind through cybernetics.

REFERENCES


