The Model of Autonomous Unmanned Underwater Vehicles Interaction for Collaborative Missions

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Abstract. Results of the work carried out by Saint-Petersburg State Marine Technical University in the framework of the project, connected with complex researches in maintenance of creation of a multi-agent sensory-communication network based on marine robotic platforms (MRP), are presented. In the context of the mentioned works, creation and testing of communication protocol for µAUVs with hydroacoustic modems is proposed. The article describes steps of protocol creation: from mission planning to modem control and modeling with digital imitation model testing (Solving the task of monitoring the seabed area). Within the framework of the concept of a “budget”, limited serial product, functional systems/modules of µAUV are worked out, taking into account the availability of equipment and components (concerning required technical characteristics and their cost). For the selected external appearance and design dimensions of the device, the simulation of hydrodynamic, signal power and energy characteristics were performed. Within the framework of the project, a software and hardware architecture of the information system of the vehicle was developed, as well as a model of interaction between the µAUV, the wave glider and control center. The work results in proposal and testing of µAUVs communication through the water. Simulation results of implementing mission by a group of developed µAUVs can be modeled by ground robots with some software limitations. Based on the results, ways for further work on the subjects are being determined.

Keywords: Marine multi-agent sensory-communication network
Communication protocol · OSI · Contract Net Protocol
Marine robotic platform · Micro autonomous underwater vehicle
Group missions

1 Introduction

Development of autonomous unmanned underwater vehicles (AUUV), that is underwater robots, represents one of the most dynamically developing areas of elaboration of foreign naval technologies, universities and commercial firms. World leaders in the development of the AUUVs are the United States, Great Britain, Canada, France, Germany and Japan. The number of devices created abroad has exceeded 9000 [1].

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The main difference of AUUVs from terrestrial robots and UAVs is large movement resistance, ability to move in 3D, hang (in contrast to UAVs) and a strong limitation of the communication speed, range and positioning.

Functionally, all AUUVs contain mission control system, information system, motion control system, sensor system, mechanical and power system, communication system and payload (Fig. 1) [2].

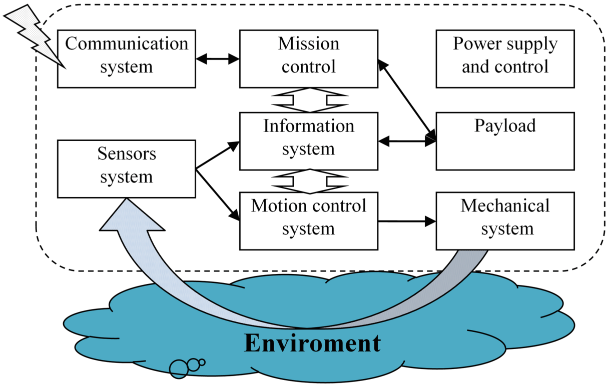

Fig. 1. Functional diagram of AUU.

It was shown in the researches [3–7] that this problem is most effectively solved by decentralized distributed network-centric systems of group control. Let us consider the system of network interaction of AUUV group and the ways of its modeling and prototyping.

The model of interaction of any autonomous robots, including AUUV, can be described by the 7-level model of the OSI network interaction, depicted in Table 1 [8].

Table 1. Levels of network interaction in OSI model.

Application layer	Mission control, arbitration, voting, task planning
Presentation layer	Presentation of agent data for communication purposes (task list, voting, arbitration, task distribution)
Session layer	Forming of communication session, choosing of a subscriber, communication route planning
Transport layer	Data communication protocol between the agents
Network layer	Logical addressing, routing, message delivery confirmation. Protocols ICMP, SS7
Data link layer	Package formation, check sum, physical adressing. Protocols x.25, ARP, DSS
Physical layer	Hydroacoustic modem, OFDM, …

The exchange protocol between agents must perform the following functions [9]:

1. Access to the network (Physical and Data link layers of the OSI model). A hydroacoustic modem is used for the physical layer and X.25 - for the link layer. These protocols allow to generate messages as addressed ones (for one subscriber), and as broadcasted or multicast (for all available).
2. Network (batch level). The basic protocols are ICMP, IP, SS7. If a message from one agent to another cannot be transmitted directly due to the signal propagation features and to a long distance, other agents located between these two subscribers may pass it along the chain.
3. Application layers (Application, Presentation, Session, Transport layers) are responsible for the group application of network agents and mission planning and control.

Currently, autonomous agent communication languages, including group AUUV, continue to evolve actively, new algorithms and methods, methods for resolving conflicts in a group are emerging to increase the effectiveness of this group. Since compatibility is the defining agent characteristic, in the development of MAS, standardized communication is of great importance [8, 9]. The main objects for standardization are: agent architecture, agent interaction languages, agent interaction protocols, agent knowledge, agent programming languages. When developing its own multi-agent network of underwater and surface robots, the Contract Net Protocol (CNP) [9] developed by FIPA was chosen, with modification in which abstract tenders were replaced by virtual money relations.

Exchange between agents at the application level involves the distribution of tasks among agents, resolving conflicts when sharing resources, informing about the task status change and so on. These messages are high-level and universal. Communication languages at the application level can be identical for underwater robots, terrestrial or flying.

But for the correct modeling of entire network interaction system, it is necessary to provide a correct simulation of the network formation level and of the network access level. If network access level is determined by parameters of the hydroacoustic modem (hydroacoustic modem is the most long-range data transporter for wireless communication under water), level of network formation depends strongly on the features and limitations of this hydroacoustic modem.

A time delay in implementation of the exchange protocol significantly depends on speed of delivery of the message to the addressee and receiving confirmation. So, when using a radio communication, delays for sending a message to a destination located at a distance of 1.5 km will be 5 μs, but using a hydroacoustic communication channel it will be 1 s. In the protocol shown in Fig. 2, at least 3 transmissions are required to start the work by the private trader, that is, if the delay for transmitting one message is 1 s, the total delay will be 3 s. And this is only for the information exchange between two agents. Therefore, when exchanging messages between AUUVs under water, it is necessary to minimize the number of requests and responses to obtain an efficient solution.

In the case where the message is impossible to deliver directly from the sender to the recipient, it is necessary to support resending of the request by agents that are not recipients, but are available for reception from the sender. This protocol should also minimize the number of messages to save time.

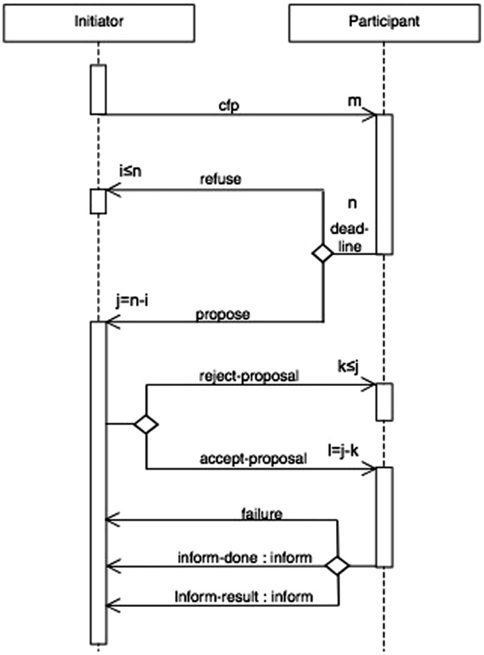

Fig. 2. Exchange protocol Contract Net Protocol.

2 Routing

Nowadays, there are no strict specifications for a handover implementation ("seamless" movement of correspondent agents between the transmitter and the receiver) [8–10]. However, to provide such a transition, special procedures for scanning the ether and joining ("association") are provided. The implementation of handover in networks can be carried out in various ways, for example, based on the Radius protocol or under control of an intelligent wireless controller, that organizes a "tunnel" when the client moves to the service area of a neighboring access point. The 802.11k specification describes procedures that allow an agent to select an access point (intermediate agent) to which one should connect to create the current connection (Fig. 3). Figure 3 shows the possible lines of communication between agents.

Considering traffic between agents within a session as a function of the amount of data transmitted $S^D(t)$, session on the time interval $[T_b; T_e]$, $T_e > T_b$ could be described by the vector

$$S^D = [S_1^D, S_2^D, S_3^D, \ldots, S_M^D],$$

breaking the interval of observation $t \in [T_b, T_e]$ into M incrementing segments.

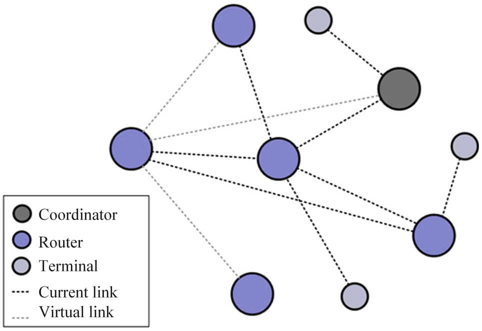

Fig. 3. An example of a self-organizing agent network structure.

Moreover, the elements of the S^D vector are such that,

$$S_i^D = \begin{matrix} t = T_b + (i+1)\Delta t \\ t = T_b + i\Delta t \end{matrix} \Big| \sum_{K=1}^{K_i} S_{i,k}^D, \\ i = 0, 1, \ldots, (M-1),$$

that is, each element of S_i^D represents the sum of the sizes of $S_{i,k}^D$ (or quantity) of packets transmitted within this session in the i-th time interval Δt. The vector S^D itself is a histogram of traffic on the time axis, and the smaller the interval Δt, the closer this histogram to the real function $S^D(t)$.

When it is necessary to send messages through correspondents (when it is not possible to directly transmit the message from the source to the receiver), the problem of optimal routing appears, that is, the formation of the transmission path, which requires minimal time and energy resources.

The mechanism of the "logical distance" allows the source and the nodes located on the request path to select the minimum "logical distance" of the route from the source to its destination as shown in Figs. 4 and 5.

In Fig. 4 it is seen that the broadcast request from I to A cannot be delivered, since I is bounded by the communication distance. Therefore, the request must be retransmitted through intermediary agents. An example of finding the optimal route is shown in Fig. 5. Agents 2 and 4 can send a message to agent A, but the logical distance from agent 4 to A is less (signal strength is greater). Therefore, this route is preferable.

The described basic algorithm is efficient and versatile, can work in dynamic conditions for automatic re-routing, and therefore it is recommended to use it to find the relay route.

For example, for the purpose of site surveys, each indexed site is a profit. Resources for the survey - direct costs. Simple work on time and loss of resources when moving through already surveyed areas - fines. To bring all the parameters to a uniform dimension, it is convenient to recalculate them into conditional energy units:

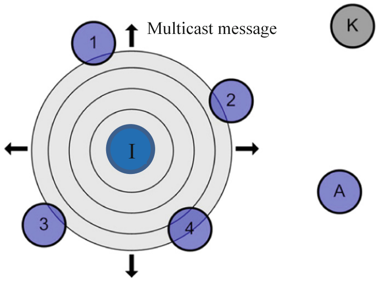

Fig. 4. An example of a broadcast request in an agent network.

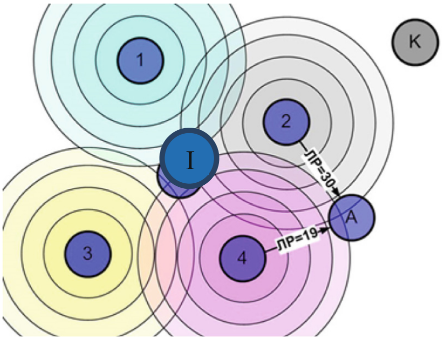

Fig. 5. Finding the optimal route for relaying

$$U = k \cdot \sum_{i=1}^{N} X_1 - \sum_{i=1}^{M} P_i - \sum_{k=1}^{M} Z_k,$$

where U is the budget of the agent, k is the incentive factor for the work performed, X_i is the work done on the sites, P_i is the additional costs for the inspection of the sites, Z_k – fines.

To simulate the interaction of AUUV in a group, it is necessary to determine which parameters will have a communication channel, namely hydroacoustic communication. From the general communication theory (Shannon's theorem) [8], it is known that the limiting communication rate between two subscribers is limited by the bandwidth of the frequencies used and the signal-to-noise ratio as:

$$C = B \log_2\left(1 + \frac{S}{N}\right),$$

where C – bandwidth of the channel, bit/s; B – bandwidth of the channel, Hz; S – total signal strength over the bandwidth, W or V^2; N is the total noise power over the bandwidth, W or V^2.

Unfortunately, in hydroacoustic low frequencies can be hardly emitted by small antennas, and high frequencies are rapidly decayed, so frequencies of tens of kilohertz are used to transmit information at distances in units of kilometers (range of small, autonomous robots), and the bandwidth is not more than an octave. The structure of the dependence of the maximum communication distance on the frequency of the communication system operation is shown in Fig. 6.

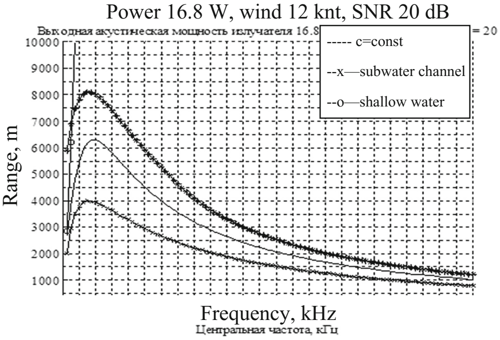

Fig. 6. Dependence of maximum communication distance from operating frequency.

Since in the marine environment supply multipath propagation of the signal as a result of salinity heterogeneity, density and temperature instability, the superposition of all possible rays comes to the receiver, which can be summed up both in phase and in the opposite phase, that is, by subtraction. This causes fading in the communication channel. The impulse response of such a channel with fading looks like

$$h(t) = \sum_{m=0}^{L-1} h_m e^{j\Phi_m} \delta(t - \tau_m),$$

where h_m has a Rayleigh distribution and F_m has a uniform distribution.

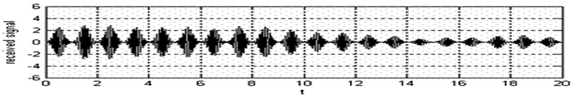

Fig. 7. An example of a fading multipath signal on a receiver.

An example of a signal with fading is shown in Fig. 7:

The following equation is used to calculate the power at each rectifier:

$$Q(n) = \frac{e^{-\frac{nT_c}{T_d}}}{\sum_{n=0}^{L-1} e^{-\frac{nT_c}{T_d}}},$$

where T_d is the damping constant, which is assumed to be *1* ms. The standard deviation of noise sources for each track has the form:

$$\sigma_n = \sqrt{\frac{Q(n)}{2}}, n = 0, 1, \ldots, L - 1.$$

Many communication channels are modeled as multi-beam channels with Rayleigh fading, having a pulse characteristic *h(k; l)* and representing a delay line with taps, where the *k-th* coefficient is a Gaussian random process with a variable time *l*. In [3], a stationary uncorrelated scattering model is proposed to facilitate the description of channels with fading. This model, which is suitable for most radio channels, suggests that signal constituents arriving with different delays are uncorrelated and that the correlation properties of the channel are stationary. The autocorrelation function taking into account these assumptions has the form:

$$E[h(k_1, l_1)h^*(k_2, l_2)] = \delta(k_1 - k_2)R(k_1; l_1 - l_2).$$

Without loss of generality it is assumed that the greatest value of the profile of the trajectory is observed at $k = 0$, i.e. in addition, the received signal is subject to a complex-valued additive white Gaussian noise with a spectral density of power N_0.

In addition to fading in the channel, the signal is also distorted by noise. The noise dispersion depends on the E_b/N_0 ratio, the encoding rate *C*, and the spectrum efficiency. The noise dispersion has the form

$$\sigma_n^2 = \frac{1}{2n}\frac{1}{C}\left(\frac{E_b/N_0}{10}\right).$$

where *n* is the modulation intensity of the digital modulation scheme used.

The development of AUUV interaction algorithms for group interaction is a very complicated and costly operation [13–15], since the procedure for launching, controlling the operation and collection of the AUUV group requires the use of a large number of participants, the accompanying vessel and the need to debug possible errors with the risk of losing costly devices. Numerical simulation on a computer may not cover all possible situations that agents fall into [15]; therefore, it is necessary to use a simple, reliable and inexpensive way to debug algorithms for network interaction of mobile robots. In this way, it is the use of terrestrial mobile robots that perform a mission similar to AUUV group, for example, to search for objects of a given shape and color on a specific territory [11]. Such robots are equipped with an autonomous positioning system and information transmission with software server delays and bit errors to simulate hydroacoustic communication channel [12].

An example of a mission performed by terrestrial robots in the process of modeling the AUUVs group is shown in Fig. 8. Robots of different types (“R” - repeaters, “S” - searchers) must go from the base (“B”) to the search area, agree with each other on the trajectory of the movement so that it does not interfere with each other to effectively examine the territory, find the object sought and call the robot “Y” from the base (destroyer).

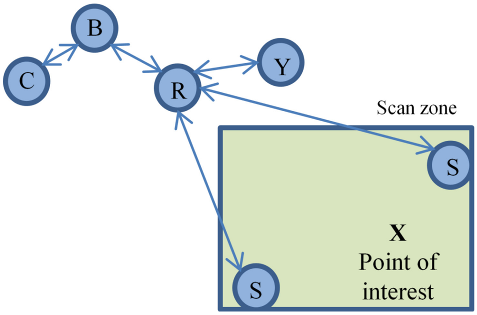

Fig. 8. An example of a team of interacting mission robots.

3 Conclusion

Thus, for modeling the interaction of AUUV in the group, it is necessary to implement by software all seven levels of network interaction OSI. But if the levels 2..7 are logical and are easily simulated on both computer models and on any movable robots, then level 1 (physical level of interaction) has a number of features and limitations that need to be taken into account in order to model the hydro acoustic interaction itself:

1. Distribution delays associated with low rate of transmission.
2. Limit on the maximum communication range determined by the absorption and scattering of the acoustic signal at the modem operating frequency, as well as the presence of interference.
3. Random fading effects as a consequence of multipath propagation.
4. Bit error messages transmitted as a result of interference.

For example, if the range of the modem is 1..2 km, the depth is 50 m, the soil is dense stony, the temperature is *6..8*°, salinity 12‰, then the following parameters can be used in the model:

1. The propagation delay depends only on the distance and speed of sound in water at a given temperature and salinity: $t = r/c$, where r is the distance, c is the sound velocity ($\sim$1480 m/s).
2. Random fading effects in hydroacoustic are introduced as an anomaly coefficient, which can take values from 0 to 2..3 by the Relay distribution with $\sigma = 1.0$.

3. Bit errors are simulated by randomly replacing a certain number of bits in the transmitted packet, and the number of bits is set by the BER parameter, calculated from the signal-to-noise ratio in current conditions: $N = BER * len$, where N is the number of bits to be spoiled, BER is the intensity of the errors taken from Fig. 3, len is the packet length in bits. Then the range over the distance is determined by the distance at which the intensity of the bit errors during the transmission becomes unacceptable, for example, more than 10^{-1}.

Thus, it is possible to obtain a model of information transfer between underwater small-sized robots, close by parameters to the real conditions, and to use it in the development of interaction protocols taking into account all the main constraints that affect the operation of acoustic modems in the aquatic environment. And the algorithms of the interaction of a robot group can be debugged on mobile surface robots that are easier to trace, read from them information, which are many times more reliable and cheaper than AUUV's designed for group application, in order to then use the debugged algorithms on these AUUV.

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