

Algorithms for Establishment and Reconfiguration of Optical Information Network for Multi-Agent Robotic System

Alexey Kirianov* and Konstantin Nabojev

Laser Technology Centre, Ltd., St. Petersburg, Russia; alkirianov@yandex.ru, k.nabozhev@ltc.ru

Abstract

Background/Objectives: Multi-agent Robotic Systems (MRS) with supervisory control can solve important practical tasks. For efficient MRS operation it is required to provide high speed (over 1 Gb/s) wireless communication between its agents. **Methods:** The implementation of the required high-speed data interchange in a multi-agent system is only possible when using wireless optical links. Low divergence of laser radiation is an important advantage of these lines, but it greatly complicates the task of establishing and reconfiguring optical information systems. **Findings:** The paper discusses possible algorithms for solving problems of the establishment and reconfiguration of an optical information system with respect to MRS, which is being developed within the framework of an applied research funded by the Ministry of Education and Science of the Russian Federation. **Improvements/Novelty:** By means of dynamic reconfiguration of the network the proposed algorithms for optical information network construction enable to provide reliable data transfer between the MRS agents at their mutual movement and link loss variation.

Keywords: Algorithm for Establishing an Optical Information Network, Communication Channel Reconfiguration Algorithm, Communication Terminal, Multi-Agent Robotic System, Laser Beacon, Optical Amplifier, Optical Information System, Signal Laser Channel

1. Introduction

MRSs are designed to meet the challenges of exploration and monitoring of territories, deployment of equipment in conditions that exclude direct human involvement (extra-planetary stations, land areas with high levels of contamination, etc.), the traffic flow organization in the unmanned mode, etc.¹⁻⁶. Operation of such MRSs requires each robotic system agent to receive and process in real time mode a large amount of information about the environment and high speed (over 1 Gb/s) wireless exchange of the information with a network-centric control point and between the MRS agents. The implementation of such high data rates in systems with a large number of receiving and transmitting facilities is possible only when using wireless optical links.

The fundamental difference between wireless communication optical lines and currently used radio frequency

links between the robots and the control center is a high carrier frequency and a small angular divergence of laser beams (from few millirads to tens of microrads)⁷. Such a low divergence of laser radiation is an important advantage of optical communication lines in terms of the size and weight of equipment, necessary transmitter power, secrecy, and immunity, but it greatly complicates the task of establishing and reconfiguration of an optical information system, providing stable channels of communication between the MRS agents in motion and the control center.

The problem of establishing and maintenance of an optical information network contains two most difficult tasks: establishing and holding an optical link between the terminals, of which either one or both are moving cross-country, as well as the optical network reconfiguration in case of loss or re-establishment of optical channels connection playing an important role in the transmission of large amounts of information.

*Author for correspondence

The first task will depend upon such technical parameters of an optical communication terminal in a mobile MRS platform as the divergence of the transmitter radiation, amplitude-frequency characteristics of the baffles providing angular stabilization of its optical axis, the diameter of the mobile platform wheels and the size and weight of the wheelbase, the displacement speed and effectiveness of the depreciation means, the signal measuring and processing time and the optical axis misalignment with the direction of the second communication channel terminal. Analyzing the effect of these parameters on the efficiency of maintaining the link in operating condition allows formulating technical requirements to the parameters of the platform and the terminal.

The success of the second task depends largely on the terrain and the objects packing density on it, preventing the establishment of direct optical communication lines in any significant distance (trees, shrubs, boulders, buildings, even grass, if its length exceeds the height of the terminal mounted on the mobile platform). On the other hand, a high probability of the regular loss of all optical channels for a single agent network moving on difficult terrain makes demands of a high degree of the agent autonomy, given the fact that the transfer of a large amount of visual or location information by radio is virtually impossible to control by the operator. As a consequence, the establishment of the optical network algorithm must be dynamic, reconfigurable, depending on a particular configuration of nodes and channels, using numerical modeling techniques aimed at forecasting the change processes in the optical channels transmission capacity.

In other words, the algorithm for dynamic reconfiguration of an optical network makes its demands to navigation, orientation, and environment monitoring tools mounted on mobile platforms and to stationary control centers, where optical communication terminals are installed. These requirements, coupled with the requirements for parameters of mobile platforms and communication terminals, will not only determine the algorithm of establishing optical networks, but also the scope of practical application of MRSs.

2. Concept Headings

In developing the optical information network establishment and reconfiguration of algorithms for a multi-agent robotic system, one must take into account the specific fea-

tures of the MRS establishment. Let us consider an MRS, which consists of mobile platforms (MP) representing a load-bearing structure with wheeled chassis and mounting faces for: several communication terminals (CTs), a channel switching electronic module (SM), an electronic control module (CM), a stereoscopic annular telecamera (ATC), an omnidirectional laser lidar (LL); a coordinate metrology system module (CMS), and a changeable disposable load (CDL), i.e. the equipment used to address the targets the MRS is facing.

Communication terminals are the key element of an OIS, each of them consisting of an optical transmitter/receiver (OTR), a slewing unit (SU), and a channel switching module that provides routing data and command stream received by a CT through an optical communication channel, in the direction of the control module CM, and data and command streams generated by the CM while processing the data from the environmental parameter sensors (ATC, LL, CMS), as well as the command and data streams received by the CM via radio and from the GPS/GLONASS sensors mounted on the MP.

The optical transmitter/receiver (OTR) is a fixed assembly of three optical systems with collinear optical axes.

The first of the systems generates beacon laser radiation used for guidance, capturing and tracking the other CT designated as a connection agent. The second optical system is a laser connection transmitting channel. It consists of an SFP-module transmission channel with fiber output lead of radiation, an optical amplifier (OA) and an output collimator. The laser beacon collimator forms a beam with the divergence of 1°-3°; the connection channel collimator provides the laser beam divergence at the level of 1-2 mrad.

The third optical system represents two receiver channels with collinear sighting axes, designed to receive the signal beam with the wavelength of $\lambda_1 \sim 1.55$ micron and beacon laser radiation with the wavelength of $\lambda_2 \sim 0.85$ micron. The receiving optical system comprises an interference filter for the channel working wavelength and two lenses O1 and O2, one of which is focused on the fiber endface, through which signal light is supplied to the SFP-module receiving input, and the second is focused on a matrix position-sensitive photoreceiver, registering the misalignment of the designated CT laser beacon radiation with the receiving channel sighting axis and, consequently, with the transit channel communication

laser beam direction. The signal from the SFP-module enters the SM block, and then the CM via data bus.

The slewing unit represents a two-coordinate joint with a rotary actuator around its vertical and horizontal axes, where a pointing mirror is mounted, its light aperture of which intercepts the aperture of the transmitting and receiving laser channels. Each rotary actuator is equipped with an angular-motion transducer and is controlled by the slewing unit connected with a controlling programmable processor. The processor has an interface with the CM data bus, which serves to pass the preliminary guidance and retargeting commands to the slewing unit.

The processor also has an interface with MP vertical position sensors and a position-sensitive receiver (PSR) of the ORT capture and tracking channel, which is part of the adaptive tracking circuit that ensures holding the direction towards the laser beacon of the CT the laser communication is provided with.

Information from the environment sensors and control commands can be broadcast independently through two channels: the optical and radio ones. Moreover, before establishing the optical link, if out of the optical contact or in poor weather conditions for transmission of commands and low-speed data traffic, the radio channel is used; at the rest of the time, the optical channel with a possible doubling over the air is used.

3. Result

3.1 The Terminal Operation Algorithm

The communication cycle through the terminal involves several stages: testing the condition of the slewing unit, of the receiving and transmitting channel for their compliance with the parameters of the power supply, and the status of the catches. In case of their inconsistency of the parameters with the setting valuations, the CT operation is suspended; the test results are transferred to the stationary control point to make a decision about the CT limited use feasibility or its major failure logging.

With the routine testing course, the commands of removal from the catches are run, and the program of the CT receiving and transmitting channels sighting axis prepositioning in the intended direction is turned on. The coordinates of the CT designated for communication are sent from the MRS control point by radio to the CM and transferred to the SM by program bus.

The MRS control point generates the CT slewing unit control commands based on processing the data received from the MP (the MP construction axes coordinates and the CT pointing mirror orientation) via radio, and the data on its own coordinates and orientation derived from the sensors mounted at the control point. In the process of running the orientation commands, the rotation angle values of each CT slewing unit actuator are sent to the CM and further to the control point. If necessary, the CT pre-orientation and the subsequent mutual capture of laser beacon beams and the communication channel can be carried out while the MP is not in motion.

Preliminary pointing according to the control point commands is performed to the accuracy determined by its own position measurement inaccuracy, the target designation inaccuracy, and the measurement error of the angular position of the slewing unit sighting axis.

In compliance of the slewing unit rotational displacement with the target values, a command is generated to switch on the CT laser beacons, between which a communication channel is formed. If the laser beacon divergence and the magnitude of the angular field of view of the pointing receiving channel are higher than the pre-guidance circuit uncertainty cone aperture angle, guaranteed capture of the laser beacon beam by the cooperative CT position-sensitive receiver vision area is ensured. After that, the fine alignment adaptive circuit of laser beams axes of two designated CTs is turned on.

After confirming the capture of the signal beams by a narrow-field signal channel fiber receiver, the CM issues a command to start data transmission.

In the absence of the signal beam capture by each CT receive paths or an insufficient signal strength level, the CM generates commands to increase the signal power or reconfigure the OIS in order to transfer data to the control station through another route.

3.2 Algorithm for Dynamic Reconfiguration of Optical Networks

The MRS under consideration is similar to Mesh-networks in communication terms. At the same time, it has a number of features that define the specific nature of its functioning algorithms.

The first feature is the low reliability of optical communication channels, which implies active use of an auxiliary radio frequency.

To establish an information network requires all the grouping agents to operate in an integrated reference sys-

tem, to form which it is expedient to use a control point, which is stationary in the MRS operation period, but in case of deploying a grouping it can be relocated to a point in space providing a maximum line-of-sight range in the user's area of interest or at the boundary of a danger zone. At the same time, the major information stream is unidirectional (towards the stationary communication point).

As already mentioned, a land-based MRS along with the stationary control point (SCP) includes a certain number of mobile platforms (MPs). The optimum quantity of MPs depends on a specific task given to the MRS. It is worth noting that in a particularly rough terrain multiple SCPs can be used.

The SCP composition is determined by the tasks it solves to collect and process information, as well as to control the MRS in the absence of a broadband communication channel with the global network. The operators' workstations as part of a SCP are needed to exercise visual control over the activity of grouping agents, to adjust goals and objectives in the grouping supervisory control mode, to make decisions in cases of dispute. The SCP control module integrates all the data from its own environment sensors and the MP sensors drawing up a three-dimensional terrain map according to multiangle television and location monitoring data.

In addition to several CTs, an SCP must include means of narrow-band radio communication with the MPs for transmission of control signals when establishing communication channels in case of temporary breach of the direct visibility conditions and of individual agents working in the offline mode.

The MRS under consideration is centralized in terms of the group control strategy, since it implies supervisory control by the SCP. The basic computational resources are mounted on an SCP control module (SCP CM). The SCP CM also exercises control over the MRS in automatic mode. The SCP CM through communication channels (radio and optical information network) receives information from the sensors and devices mounted on the MP, processes the information received, and on its basis:

- Creates a three-dimensional terrain map decomposing the environment image into objects;
- Plots the coordinates of the mobile packages and orientation of their axes in the SCP reference system;
- Determines the axes orientation of the LL, ATC, CT, and CMS mobile modules structurally included in the MP, and functionally in the OIS;

- Predicts the development of the situation in the short run;
- On the basis of the current conditions and the forecast, controls the MP motion and performs reconfiguration of the OIS;
- Defines tasks for the ATC, LL, and CMS and generates appropriate control commands.

The difference between the robot grouping and the MRS under consideration can be defined as a transition from the ideology of a 'flock' or 'swarm' to the ideology of an 'ensemble', where control is delegated to the conductor situated beyond the ensemble.

3.3 The MRS Parameters Determining the Capabilities of the Network Dynamic Reconfiguration

The OIS reconfiguration capabilities are determined, first of all, with the number of communication terminals mounted on the SCP and the MP. Just mounting four or more terminals on a single MP opens up operational opportunities for dynamic reconfiguration.

In contrast to Mesh-networks, where all nodes are equal, the OIS under consideration has a network controlling node, which defines the current network configuration at the physical level. In the framework of the network current configuration, an OIS works as a Mesh-network at the logical level.

To establish a link between the two CTs takes some time for mutual guidance of communication terminals, the capture of signal beams, and communication establishment.

Since the MRS configuration and air conditions on the communication line change dynamically, the need for optical network reconfiguration occurs regularly. However, a loss of communication and a possibility to reestablish it are partially predictable; therefore, it is possible to establish alternate communication lines that are activated after the expected loss on the previously existing communication line. Furthermore, it is contemplated to actively use radio-frequency bandwidth auxiliary communication lines to transmit control commands (narrowband radio channels) and transmit data through the optically opaque media (broadband radio channels).

Thus, hyperspectrality (a link on the optical and the radio carrier), unidirectionality of the information flow body (towards the SCP), the relative predictability of a

loss and a reestablishment of the optical link between two CPs can be rated among the specifics of the OIS under consideration.

The predictability relativity is determined by the fact that in addition to the calculable factors, which include terrain, definitely shaped mobile objects, buildings, and structures, the channel transmission capacity can be also affected by uncontrollable or obstinate circumstances (atmospheric turbulence, aerosol scattering, swaying treetops, birds, etc.). A reliable transmission of information flows under these conditions can be carried out, primarily, by means of duplicating and (or) reserving the communication channels. Such an approach is possible in the case when there are 3 or more MP-borne CTs. Given the fact that one of the terminals is used to transmit information towards the SCP, the communication lines number multiplication factor in the OIS node differs from the number of MP-borne CTs per unit.

The most difficult part is the algorithm of dynamic reconfiguration (ADR) of the OIS with regard to the terrain, to the position and the orientation of the CT sighting axes, to the transmission capacity assessment of potentially established optical and radio frequency communication channels between the nodes. Thus, the ADR imposes requirements on the navigation system of mobile nodes (their position and orientation), the system of coordinate information collection (the terrain), and the system of visual information collection (the channel transmission capacity assessment).

MRS deployment begins with the stage of location survey. Figure 1 shows an example of MRS location survey. The black circle denotes the SCP, the pink one stands for the MP, the red lines denote optical links, the green ones stand for radial and blue ones - for tangential radio-frequency channels. The black dashed lines indicate the MP motion path from the stationary communication point to the deployment site.

In this example, all the MPs are directly connected to the SCP. Another extreme case is associated with the MP collocation. As a matter of practice, an intermediate configuration would most commonly occur, in which each of the radial links would consist of several segments. The number of segments can vary, but the scope of duplication and reservation will be determined by the number of tangential links. Note that tangential links may be both optical, and radio frequency.

On their runway, MPs may fall out of the SCP line-of-sight range. In this case, the MRS agents can either

go into the independent operation mode, or to carry out connection in chain order. The chain deployment feature, where each successive MP moves more slowly than the one moving ahead, is when the second and the third MP travel over the distance that has already been passed by the first MP; therefore, the information from their on-board sensor systems does not have significant value for the SCP. As a consequence, when they are deployed as a chain, the highest priority is assigned to the information from the sensors of the front MP.

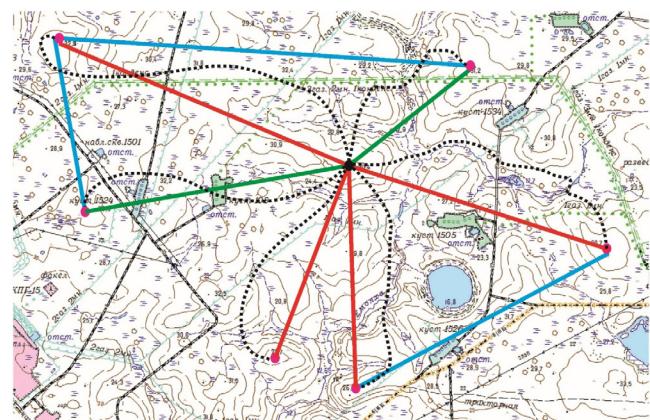


Figure 1. MRS location survey.

Figure 2 shows an example of dynamic reconfiguration of a linear optical network, when the SCP connection with the MP, located behind a timberland, can be carried out through communication lines bending round the obstacle on the left or right by a data relay. In a highly branched network, dynamic reconfiguration will be done by line switchover from one radial ray going to the SCP to the other one by means of tangential communication lines connecting the radial links like an underground belt line.

The establishment of circular communication lines around the SCP and of tangential communication lines between the MPs, situated at different radial communication channels, provides hot standby (when a channel is established, but the transfer through it does not occur). In those cases where an excessively large flow of information is going through the radial channel, to improve the reliability of its delivery it is advisable to implement communication lines duplicating, when the same information goes through both the direct radial link, and around due to transfer through the tangential link to another radial channel. Duplication is reasonable to use also in case of critical information transfer.

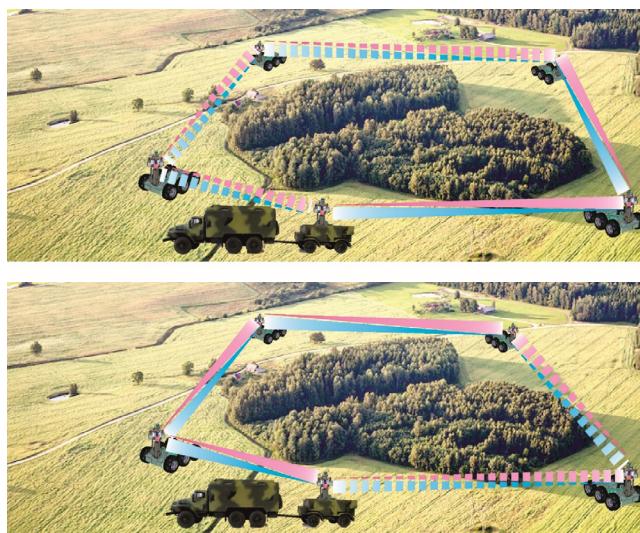


Figure 2. Dynamic reconfiguration of an optical network.

Summarizing the algorithm consideration of the OIS dynamic reconfiguration for MRS, it can be concluded that when developing an MP, all the developed environment control facilities should primarily provide the establishment and maintenance of the OIS communication channels. Without dynamic reconfiguration, the OIS efficient functioning is unfeasible, and without an OIS, an MRS becomes a usual grouping of robots. It should be noted that the functional load of MP location and television means is much wider and includes monitoring and measurement tasks, but those tasks are secondary, as the collection of information that is not promptly deliverable to the consumer considerably reduces the value of the situation operational control facilities.

4. Discussion

The above algorithms of the establishment and reconfiguration of an optical information network for a multi-agent robotic system allow formulating requirements for the composition and the content of mathematical software (MS), necessary for the MRS implementation. The composition of the MS should include:

1. A program module of front-end processing of information, pointing, capture, and switching information channels which performs the orientation determination of the information channel terminals, referrals to correspondents, the required angular displacement of terminal actuators. According to the data obtained during continuous monitoring of angular variations of the platform position, the program performs mutual guidance of the

terminals that provides mutual capture of the optical axes according to the beacon radiation.

2. The software module of the algorithm of the network entry configuration, which calculates a scheme of the quickest possible pairwise testing of communication lines between the terminals, and calculates the OIS launch configuration before deploying an MRS.

3. The program module of correspondent support and dynamic reconfiguration of the network, which provides stable channels of communication in the CT network, including extensive networks, predicts changes in the channel transmission capacity and implements dynamic reconfiguration of the network to ensure continuity of communications.

5. Conclusion

The authors have considered the problems faced by the developers of scientific software for multi-agent robotic systems with network-centric control functioning and algorithms which should be taken as a basis for the MS development.

The analyzed algorithms for establishment and reconfiguration of an optical information network and the MS implementing them allow ensuring the operation of MRSs that are able to solve important practical tasks.

6. Acknowledgement

This article has been prepared with the financial support of applied scientific research by the Ministry of Education and Science of the Russian Federation. Agreement of November 9, 2015 No.14.579.21.0128, the Unique Identifier of Applied Scientific Research is RFMEFI57915X0128.

7. References

1. Desai A, Milner S. Autonomous reconfiguration in free-space optical sensor networks. *IEEE Journal on Selected Areas in Communications*. 2005; 23(8):1556–63. DOI: 10.1109/JSAC.2005.848362
2. Davis CC, Smolyaninov II, Milner SD. Flexible optical high data rate wireless links and networks. *IEEE Communications Magazine*. 2003; 41(3), 51–57. DOI: 10.1109/MCOM.2003.1186545
3. Desai A, Llorca J, Milner SD. Autonomous reconfiguration of backbones in free-space optical networks. *IEEE Military Communications Conference (MILCOM)*. 2005; 1:1–6. DOI: 10.1109/MILCOM.2005.1579020

- Communications Conference. (MILCOM); 2004. p. 1226–32. DOI: 10.1109/MILCOM.1495119.
4. Llorca J, Desai A, Vishkin U, Davis C, Milner SD. Reconfigurable optical wireless sensor networks. Proceedings SPIE, Optics in Atmospheric Propagation and Adaptive Systems VI. 2004; 5237(1):136–46. DOI: 10.1117/12.511368.
 5. Nazarova AV, Ryzhova TP. Methods and algorithms for multi-agent control of robotic system. Engineering Journal: Science and Innovation. Moscow: Bauman MSTU Press. 2012; 6(6):93–105. DOI: 10.18698/2308-6033-2012-6-251.
 6. Lokhin VM, Manko SV, Romanov MP, Diane SA-K. Prospects of application, design concepts and problems of development of multi-agent robotic systems. Proceedings of XII All-Russian Conference on Control Problems. Moscow, 2014 Jun 16–19; 2014. p. 3810–21.
 7. Mai VV, Pham AT. Performance analysis of cooperative-ARQ schemes in free-space optical communications. IEICE Transactions on Communications. 2011; E94-B(1):1–10. DOI: 10.1587/transcom.E94.B.