Features of Establishing Laser Communication Systems for Multi-Agent Robotic Systems

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Abstract

Background/Objectives: The article discusses the requirements for optical information systems intended for use in MRSs, the necessary software composition, as well as sound technical solutions, which can be used in the development of OISs. **Methods:** The conducted analysis of the scientific and patent literature enabled to highlight the most promising technical solutions which are integrated into the proposed concept for the system construction. **Findings**: MRS operation requires the system agents to process in real-time mode large amounts of information about the environment and a high speed (over 1 Gb/s) of the wireless exchange of information with a network-centric control point and between the MRS agents, and through a large number of channels simultaneously (up to several dozen). For these reasons, in advanced MRSs the open optical channel communication should be considered as the main means of communication. **Improvements/Novelty:** The proposed concept for constructing a system is based on the synthesis of 'all-optical' circuit of open optical communication and scanning system that is typical for laser radar systems.

Keywords: Communication Terminal, Laser Beacon, Multi-Agent Robotic System, Optical Amplifier, Optical Information System, Position-Sensitive Receiver, Reconfiguration of Communication Channels, Signal Laser Channel, Tracking Circuit

1. Introduction

The development of autonomous MRSs controlled by a remote operator is regarded as an effective means of solving a large number of practical tasks. These include the tasks of intelligence and monitoring of territories, the equipment deployment 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.¹².

As MRS agents, mobile robotic modular platforms that carry an actual load in the form of environment sensors, computing facilities for processing information from the sensors, means of communication with the network agents, and working equipment for the fulfillment of targets (handling units, drilling equipment, etc.) are considered. Stationary control points are also MRS agents; they ensure processing the data, incoming from robotic platforms, and issuing commands to perform data collection operations and target missions.

Two levels of control are exercised in an MRS:

- a) a free running mode of robotic system agents according to the program recorded in the local control unit memory;
- b) a controlled operation mode of the robotic system agents according to the commands coming from a remote control station. Wherein, the control commands can be generated both by the control system itself in accordance with the automatic processing program of the data received from the robotic system agents and in the supervisory mode, when control commands are controlled by the operator.

Functioning of such MRSs requires each agent robotic system to receive and process in real time mode large amounts of information about the environment and a high-speed wireless exchange of this information both with the network-centric control point and between the MRS agents.

The body of information is the video information received from airborne visual facilities carried on the board of mobile platforms³. To ensure the control of

mobile carriers in the course of their motion, the resulting video data must be three-dimensional, which prescribes the use of stereoscopic television systems and laser location devices. Therefore, the wireless data communication between the MRS agents in real time mode requires the implementation of the data rate of over 1 Gb/s in each communication channel, and at the same time through a large number of channels simultaneously (up to several dozen).

Currently, in MRSs for wireless communication with the network agents radio networks are used, where each agent fulfills the function of a transmitter, a receiver, and a repeater of information.

The highest data rate and the bandwidth are ensured with a WiFi network. The existent 802.11g standard networks provide a maximum data transfer rate of 54 Mbit /s. The IEEE 802.11n standard, approved in 2009, allows increasing the transfer rate up to 200MB/s. Theoretically, this standard can provide data rates up to 600 Mbit /s.² It was only during the switch to the IEEE 802.11ac standard, adopted in 2014, when there appeared prerequisites to reach the data transfer rate of several Gbit/s. However, such velocity is achievable only with the use of 4 – 8 MIMO channel antennas, equivalent to a corresponding increase in the frequency band occupied by the channel.

In radio frequency systems, the interference between the adjacent carrier frequencies is a major problem of the communication frequency bands harmonization. In addition, in the radio-frequency region, the frequency licensure by special regulators is required. Radio-communication channels do not provide the secrecy of communication channels necessary in some applications; they are susceptible to natural and artificial electromagnetic interference. For these reasons, in the advanced MRSs, communication through an open optical channel should be considered as the main means of communication.

The main difference between an optical communication channel and a radio communication channel is associated with a large difference in the wavelengths. The radio wavelengths are thousandfold as long as for the optical communication at the wavelengths between 700 nm and 1600 nm, corresponding to the atmospheric transparency windows.

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The main difference between an optical communication channel and a radio communication channel is associated with a large difference in the wavelengths. The radio wavelengths are thousandfold as long as for the ones for optical communication at the wavelengths between 700 nm and 1600 nm, corresponding to the atmospheric transparency windows. As a result, optical communication provides a much wider modulation bandwidth. In the radio frequency and microwave systems, the bandwidth can reach up to 20% of the carrier frequency. In optical communication systems, even if the bandwidth of 1% of the carrier band (10¹⁶ Hz) is used, the achievable bandwidth will amount to100 THz, which is 100 000 times as much as in radio systems.

Optical communication provides a much smaller beam divergence. The beam divergence is proportional to λ/D , where λ stands for wavelength and D is the radiating aperture diameter. Therefore, the optical beam divergence is much smaller than the microwave beam divergence. With a fixed transmit power, this leads to a large increase in signal strength at the receiver. In addition, the small divergence of light (laser) beams provides high secrecy of the communication channel and hinders jamming.

Optical communication provides a significant reduction of the transmission power and the weight of a communication system. Increasing the beam intensity by lesser divergence allows, at a given power of the transmitter, using a receiving antenna of a smaller diameter without loss of the gain (the antenna gain is inversely proportional to the square of the wavelength). The typical size of an optical system is 0.1 meters compared to 1.5 meters for a radio antenna. Optical systems to date do not require frequency licensure. This reduces the cost and time of communication networks deployment.

Communication via the optical channel is difficult to detect using spectrum analyzers and level radiation gauges, as optical radiation is narrow-gauge, and it is difficult to introduce a sensor into the transmitted beam. Light is not able to penetrate through dense barriers, which impedes hidden communication interception. In addition to the above listed, optical communication has the following advantages: a) it is easy to expand and reduce the information network segment size; b) it has a small size and weight; c) it provides for simple and rapid deployment; g) a wireless optical link can be used where the fiber-optic communication lines cannot be applied.

2. Concept Headings

In developing MRSs, one should take into account a number of the Optical Information Systems (OIS) implementation features.

Firstly, in connection with the laser beam divergence of milliradian fractions there is a problem of establishing and maintaining a stable communication channel between the remote terminals, of which either one or both are in cross-country motion.

Secondly, a rapid recovery of communication in its failure due to a physical obstacle to the laser beam path (uneven terrain, tree branches, birds, etc.), or loss of communication in the channel with strong air turbulence is a problem.

The first task solution will depend upon such technical parameters of the optical communication terminal mounted on a mobile platform as the transmitter radiation divergence, amplitude-frequency angular actuators providing angular stabilization of its optical axis, the diameter of the wheels and the size of the mobile carrier base, its displacement speed and the efficiency of amortization means, the time measurement and the signal processing of the optical axis deviation of the transmission channel communication terminal from the direction of the second communication terminal receiving channel optical axis.

The success of solving the second task depends on the terrain and the packing density of objects on it, preventing the establishment of direct optical links at any significant distance (trees, shrubs, boulders, buildings, even grass, if its length exceeds the height of the terminal mounted on the mobile platform).

Robotic system multi-agency in this respect is a significant advantage, since it allows implementation of the OIS dynamic reconfiguration by forwarding data by other routes, inclusion of the OIS intermediate agents in the relay mode, MIMO-configuration of communication channels. The possibilities of organizing an optical network significantly increase even on difficult terrain in the case of using unmanned aerial vehicles as MRS agents, which is realizable in the case of a land-based system.

On the other hand, a high probability of regular disappearance of all optical channels for a network agent, moving on difficult terrain, demands a high degree of each agent's autonomy, given the fact that the transfer of a large amount of visual or location data by radio is virtually impossible to control by the operator. As a consequence, the OIS's algorithm establishment must be dynamic, reconfigurable depending on a particular configuration of nodes and channels, and using numerical simulation techniques aimed at forecasting change processes in the optical channels transmission capacity.

In other words, the algorithm for dynamic reconfiguration of an optical network makes certain demands to navigation, orientation, and environment monitoring tools on all platforms and fixed stations, where optical communication terminals are installed. These requirements, combined with the requirements for terminal and platform parameters, do not only define the technical solutions used in the development of optical networks, but also the independent MRS application algorithms.

In contrast to the known OISs used in the wireless fixed communication technology, the OIS as part of the MRS should not only ensure maintaining the data link under conditions of external disturbances, but also its establishing.

Establishing a communication channel includes the phase of the communication terminal optical axes pre-orientation with the fixed communication station commands sent via radio, the wide-angle targeting channel capture phase according to the laser beacon radiation, and the phase of fine alignment of the sighting axes of receive and transmit channels of two communication terminals forming the optical communication channel. Not until then the tracking circuit turns on, providing the communication hold.

The accuracy of communication terminal pre-orientation according to the calculated data on the location of the MRS agents on the ground and the spatial orientation of their building/construction axes is no better than the angular degree units. The calculation accuracy determines the required viewing field of the targeting channel.

The required pointing accuracy is determined by the required accuracy value of the sighting axes alignment of transmit and receive signal paths of the two communication terminals forming an optical communication channel. At the divergence of the transmitted signal beam Ω , the required accuracy of alignment of the axes is (0.1-0.3) Ω . Since the divergence reduction decreases the required laser radiation signal power, in the current land-line communication the OISs beams with a divergence of less than 1' are used⁴, so the requirements for the sighting alignment precision are quite stringent.

If in the OIS fixed communication compensated angular disturbances are characterized with the frequencies of 0.5 - 1 Hz⁴, in the MRS with the agents moving over rough terrain at a speed of several km/h, the angular disturbance frequencies may exceed 10 Hz. Consequently, in OISs it is necessary to provide for MRSs a high speed sighting axes alignment error correction, which imposes stringent requirements both for the speed and the accuracy of the optical deflectors used to align the axes, and on the parameters of the angular misalignment sensor.

The peculiarity of the OIS as part of the MRS is also a wide view angle in terms of the azimuth and the elevation angle, inside of which highly dynamic agility angular repositioning of the communication terminal sighting axis must be ensured while establishing a communication channel and data transfer in motion. Depending on the number of the communication terminals on one carrier, the required view angle in azimuth may vary from 90° to 360° and in elevation from -20° to 90°.

It is also essential that more stringent requirements are made for the OISs as part of MRSs in terms of weight, size, and power consumption than a to a communication terminal used in wireless fixed communication.

Using a stand-alone MRS requires a software system that provides high-speed data exchange between the MRS agents using OISs; processing of the information on the environment received from the MRS agents obtaining it from sensors mounted on the mobile agents and the fixed stations; as well as processing the information and executing the commands coming from the supervisor.

The OIS software package should provide pointing, holding, and tracking the designated communication terminal during a communication session between two mobile packages or between a mobile package and the fixed station. In addition, the OIS software system must provide the laser optimization with account for the system of priorities defined by the MRS tasks, attain the advantages of a multi-agent network, consisting in the possibility of transferring data over a distributed network of laser communication lines, the possibility of changing the current MRS configuration (reconfiguration) and changes in the relative criteria weights of the network topology optimization during supervisory control. The software system should also provide the system operation software emulation (simulated mobile package movement, change in atmosphere parameters, etc.) and the system condition monitoring (nodes and connection layout, the quality of communication in the channel).

Reconfiguring communication channels and data redistribution through the channels is carried out in order to increase the reliability of the optical connection in case of optical contact loss, changing atmospheric conditions or failure of communication equipment. Using dynamic reconfiguration of optical communication open lines network nodes using the physical and logical layers of control can significantly increase the scope of using the communication line.

At the physical layer, reconfiguration is achieved by the use of pointing, recognition, and tracking systems; at the logical level, it is provided by the autonomous reconfiguration algorithms and heuristic algorithms for establishing communication line topology. In the course of reconfiguration, the control commands and, if necessary, datasets are forwarded through the other operating channels, optical or low-speed channels^{5–10}.

3. Results

The above requirements for the OISs for MRSs were taken as a basis of the OIS development within the framework of the Applied Research (AR) 'Development of software and hardware to establish an optical network for ground and space-related application', which is an integral part of a comprehensive Applied Scientific-Research and Experimental Work (ASREW) on the following subject: 'Development of mechatronic and photonic technologies for unified multi-agent autonomous robotic land-based and space-based systems'. The AR is being done by 'Center of laser technologies' LLC, the ASREW is being done by Russian State Scientific Center for Robotics and technical Cybernetics under the Federal Target Program 'Research and development on priority directions of Russia's science and technology sector development for 2014–2020'.

Let us consider the main designing solutions for OIS nodes implemented in course of the AR.

3.1 The Main OIS Blocks

Figure 1 shows a functional block diagram of the OIS main assembly, i.e. a communication terminal. The assembly comprises three main blocks:

- Communication node, which contains signal beam laser sources and a laser beacon, slewing unit laser and actuator drivers, and controllers that in accordance with the program implement the guidance and tracking of a communication terminal, as well as OIS configuration according to the control point commands;

- Optical node, which includes transmitting collimators of the laser beacon channel and the signaling channel, and a dual receiving channel lens. The first channel of the lens, using a position-sensitive receiver based on silicon CMOS matrix, provides registration of angular misalignment of the received laser beacon beam and the lens sighting axis. The second channel maintains reception of the data transmitted by the signal laser beam. The multimode fiber end is the receiving aperture in the signal channel. Using the dual-channel receiving channel lens circuit with a common entrance aperture for the channels allows minimizing the light size of the pointing mirror.

- Slewing unit node (SU), which provides angular orientation of the sighting axes of collinear receiving and transmitting communication terminal optical paths over a distance in order to ensure capturing the laser beacon beam of the designated CT-correspondent, combining its own sighting axis with a referral to the designated communication terminal, and supporting the designated communication terminal during a communication session both in a steady state of the MRS agents and when in motion.



Figure 1. Functional block diagram of the OIS communication terminal.

All the known wireless laser communication systems use a slewing unit in the form of an angularly controlled carrying platform where the receive path lenses and the transmission path radiation collimators are mounted. Since in the stationary laser communication systems disturbing frequencies are small (~1Hz), and turning angles do not exceed 3°, the development of such slewing units is not difficult.

However, in passing to the OIS development for MRS, the disturbing frequencies increase by an order of magnitude, and the turning angles reach 360°. As a result, the carrying platform alternate design where optical components weighing several kilograms are mounted, even when using powerful driving engines, does not provide the required speed and running accuracy. With the large platform turning angles, the problem of looping cable connections and optical joints between the base and the SU platform turns out to be significant.

In the studied OIS, the SU in the form of a scanned pointing mirror is used, to which normal transmission channels laser beams are directed and the receiving channels sighting axes parallel to them, at an angle to its surface, is used. With characteristic for optical communication at a distance of 1-2 km light diameters of receiving lenses of 40-50 mm, the pointing mirror is elliptically shaped, with the overall dimensions of 50x100 mm², and weighs as much as 0.1 kg. With such a weight, attacking small disturbances at a frequency of 10 Hz requires a relatively small driving capacity. Moving at high angles while pointing does not require a high rotational velocity, as the maximum speed of the MRS agents on the surface is below 10 km/h.

Using a pointing mirror eliminates the problem of looping cable connections and optical joints (except for current lead to the pointing mirror elevation actuator, which is implemented by means of a standard circular current collector).

Figure 2 shows the general layout of a communication terminal with indication of dimensions. The communication terminal consists of a fixed base and a cap rotatable in the azimuthal direction around the vertical axis of base symmetry. There is a plane mirror inside the cap, scanned in elevation. The optical elements of the transmitting communication terminal channels, of the dual-channel receiving lens, and photoelectric receivers are mounted inside the fixed base and connected to the switching node with the system of fiber-optic and copper cables, which are not exposed to dynamic bending and torsion stresses characteristic of the supporting slewing unit alternate version. The only wired rotating feedthrough transfers current to the windings of the mirror scanning actuator drive coil of the pos. 17. The azimuth rotation of the mirror with a protective cap mounted on a radial support bearing of a large diameter is carried out by the engine of pos. 20 via a gear unit.



Figure 2. General layout of a communication terminal.

Such a communication terminal design allows mounting on a small-size hardware mast ground of mobile robotic platform up to 4 communication terminals, providing connection through 4 laser channels simultaneously if needed. The switching node is expedient to make single for the communication terminals on the platform, mounting it inside or outside the body.

3.2 OIS Mathematical Software

The pointing, capture, and tracking program is implemented as three modules:

 the main control program based on a single-board computer, synchronizing the operation of all the communication terminal subsystems;

- the communication terminal mathematical software based on a single-board computer, carrying out a video data stream reception from a TV camera, its processing, object search, mass center calculation and the computation of the objects misalignment in relation to the center of the frame;
- 3) The PLD mathematical software that implements the scanning mirror actuator driver function.

The mathematical software of forecasting the communication terminal position dynamics, the information preprocessing, and the pointing information channels switching (hereinafter referred to as MS) is a high-level software system that communicates with the fixed station via an interface module. The main MS objectives are to construct a graph of available MRS agents based on their communication terminal spatial arrangement and orientation, the optimization of the OIS topology and the communication channels routing to ensure the required information flow, the communication terminal pointing angle calculation to open communication channels necessary for the MRS functioning.

The MS of MRS dynamics forecasting, information preprocessing, and pointing information channel switching consists of:

- The main program controlling the operation of the individual MS software modules.
- Software modules for communication network calculation.
- Graphic modules of display of the switching node location and the communication network topology.
- The OIS configuration control module.
- A software module emulating the communication terminal motion and the MRS work.

The MS has been developed in LabView graphical programming environment. Executable modules diagrams, presented in the graphical G language, are the program source code. The MS modular structure allows including only the modules necessary for specific purposes in the framework of the executable program.

4. Conclusion

Thus, the analysis shows a promising outlook for the application of wireless optical communication lines in the

development of multi-agent robotic systems. A number of specific requirements for the composition, parameters of nodes, and the developed equipment software should be taken into account while developing optical information systems for the MRS. The incorporation of these requirements leads to the communication terminal architecture, comprising a slewing unit on the basis of the pointing mirror scanned in azimuth and in elevation, stationary receiving-transmitting optical unit, and the switching unit mounted inside or outside the mobile platform body, which supports all the communication terminals installed on each mobile platform or stationary control point.

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