Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 100 (2015) 765 – 772

Procedia Engineering

www.elsevier.com/locate/procedia

25th DAAAM International Symposium on Intelligent Manufacturing and Automation, DAAAM 2014

Development of the System of Telecontrol by the Multilink Manipulator Installed on the Mobile Robot

Filaretov Vladimir[a,b], Katsurin Alexey[a,b,]*

[a] *Institute of Automation and Control Processes, Vladivostok 690041 Russia*
[b] *Far Eastern Federal University, Vladivostok, 690990 Russia*

Abstract

This paper describes the system of semiautomatic position telecontrol by the multilink manipulator installed on the mobile robot. The operator uses a special setting device for control. The telecamera which forms the image on the operator's monitor is installed on other mobile robot. This camera can rotate about two mutually perpendicular axes. The system of telecontrol makes it possible to automatically take into account the spatial orientation of television camera. The working algorithm of the computing system is proposed and examined. This algorithm forms control signals for drives of all degrees of freedom of the manipulator. The results of executed experiments confirm effectiveness of developed system.

Peer-review under responsibility of DAAAM International Vienna

Keywords: Mechatronics; multilink manipulator; telecontrol; movable camera; mobile robot

1. Introduction

Now the creation of robotic complexes intended for the prevention or elimination of consequences of accidents and emergency situations on various objects is topical problem. The using of mobile robots for the current monitoring of hard-to-reach or dangerous places for the person is also expedient. The main feature of works in extreme conditions is badly ordered and nondeterministic environment. The information about it is incomplete. This information can be dynamic and unpredictable. It demands continuous replenishment and update of information and

* Corresponding author. Tel.: *+7-423-2320682*.
E-mail address: katsurin@mail.ru

Peer-review under responsibility of DAAAM International Vienna
doi:10.1016/j.proeng.2015.01.430

also correction of the made decisions on the basis of newly obtained data. Besides, the executed operations usually are non-standard and rather difficult.

Therefore in such systems the method of semiautomatic control is usually used, when the operator provides motion of the manipulator grip by means of the setting device [1-9]. The operator is setting control signals on the basis of the image of working space on the telemontor screen. For effective control of a working zone of the multilink manipulator installed in the dangerous place it is often necessary to use several television cameras with various orientations of their optical axes. Also it is possible to use one television camera which has possibility to change its orientation and possibility to movement in a working zone.

However, the specified operating mode not always is convenient and not always provides high-quality performance of technological operations. In this case the operator must to consider constantly a relative position of the manipulator, setting device and television camera. It leads to big additional load on the operator. Besides, the setting device can appear in situation inconvenient for the operator during the execution of operations. Known approaches to development of systems of semiautomatic control don't allow synthesizing the effective systems working in such conditions.

Thus the problem of development of new methods and algorithms of effective telecontrol by multilink manipulators with change of orientation of an optical axis of a camera remains still topical.

2. Task setting

The task of development of system of semiautomatic position telecontrol by the multilink manipulator installed on the mobile robot is setting and solving in paper for the decision of specified problem. The operator uses a special setting device for control and sets control commands using image on the monitor. The telecamera which forms the image on the operator's monitor is installed on other mobile robot. This camera can rotate around two mutually perpendicular axes. The system of telecontrol makes it possible to automatically take into account the spatial orientation of television camera. The working algorithm of the computing system is proposed and examined. This algorithm forms control signals for drives of all degrees of freedom of the manipulator.

2 System of telecontrol by the multilink manipulator

Figure 1 shows the system of semiautomatic position telecontrol. In this system spatial motion of grip *6* of five-degree manipulator *5* is set by the operator using the special setting device (SD) *1*, which kinematic scheme coincide with kinematic scheme of manipulator. Manipulator installed on the mobile basis. The control of grip motion is carried out using its image on the screen of the telemonitor *3*. This image is received using the television camera *4*, which had two degrees of freedom and installed on another mobile basis.

Figure 1 has following designations: C_P, C_M, C_K – the systems of coordinates (SC) rigidly connected, correspondingly, with the basis of SD, the basis of manipulator and the basis of telecamera, C_i ($i = \overline{1,7}$) - the systems of coordinates rigidly connected, correspondingly, with the first link of SD, the basis of SD handle, the SD handle *2*, the first link of manipulator, the basis of grip, the grip of manipulator and the body of telecamera *4*; r_c and r_p - the position vectors of the basis of manipulator grip in C_4 and of the basis of SD handle in C_1; R_c and R_p - the position vectors of the basis of manipulator grip in C_M and of the basis of SD handle in C_P; q_M, q_K - angles of rotation of the basis of the manipulator and basis of the telecamera; q_i ($i = \overline{1,11}$) - the generalized coordinates of corresponding degrees of freedom of SD, manipulator and telecamera; l_2, l_3 and l_5, l_6 - the length of corresponding SD links and manipulator links which always lie in one plane.

It should be noted that orientation of coordinate axes of the setting device differs from orientation of coordinate axes of the manipulator, the television camera and the basis of the setting device. It is caused by a choice of the concrete equipment, whose parameters are determined by the producer.

The plane of the screen of the monitor is fixed in SC C_P. The motion of the SD handle and the motion of the image of the manipulator grip observed on the monitor screen are perceived by the operator as the motion in SC C_P (i.e. C_P and C_7 coincide for the operator).

The proposed system of position telecontrol by the manipulator (see Fig.1) can have two regimes [10]: the regime of stabilization and the regime of tracking. In first regime the manipulator is fixed in the space and the operator has the possibility to change SD configuration for more comfortable executing of subsequent operations. In the same regime the operator can change an orientation of telecamera. At switching moment from the regime of stabilization to the regime of tracking the setting signals for all drives of manipulator are formed. These signals provide the co-ordination of its position with the SD orientation and take into account the current orientation of the telecamera. Subsequently the manipulator repeats any motions formed by SD in the regime of tracking.

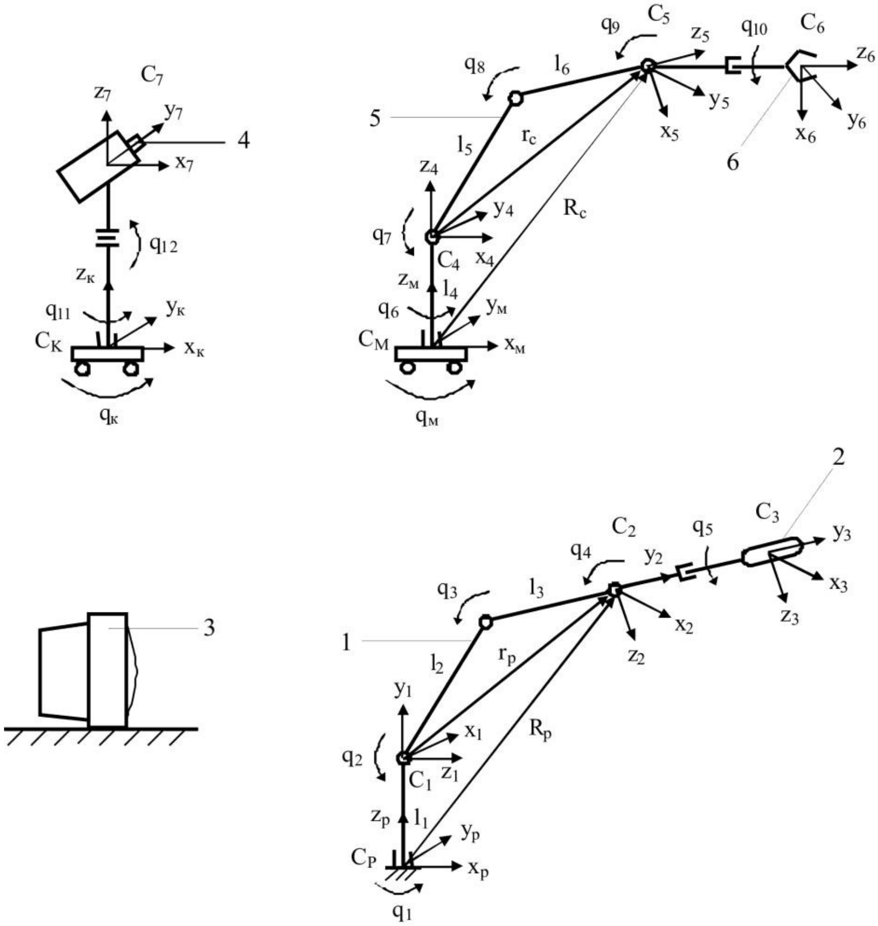

Fig. 1. The system of position telecontrol.

For the realization of the proposed method of telecontrol by manipulator the algorithm of work of the computing system was developed. This algorithm provides the formation of setting signals for drives of all degrees of freedom of manipulator.

3. Algorithm of telecontrol system

For describing this algorithm the following designations are introduced: $T_{Xi}, T_{Yi}, T_{Zi} \in T^{4\times4}$ - correspondingly, the uniform transformation matrices (elementary turnings about axes of coordinates *x, y, z* to the angle q_i and transformation); $A_j^i \in T^{4\times4}$ - the matrix of complex transformation consisting of several elementary turnings and transformation. The mentioned matrix converts some vector assigned in the rotated coordinate system C_j into the vector assigned in the fixed coordinate system C_i [11-13].

Stage 1. On this stage the angles of rotations of manipulator links (the generalized coordinates of the manipulator) are measured using the built-in sensors. The corresponding values of sine and cosine of these angles are calculated further. They are used for definition of initial value of coordinates of a vector r_p. All generalized coordinates are counting counterclockwise (in a positive direction) from its initial position. Elements of a vector r_p in SC C_1 are determined using the equations: $x_1 = 0$, $y_1 = l_2 c_2 + l_3 c_{2,3}$, $z_1 = l_2 s_2 + l_3 s_{2,3}$, where c_i, s_i, $c_{i,j}, s_{i,j}$ are $\cos(q_i)$, $\sin(q_i)$, $\cos(q_i + q_j)$, $\sin(q_i + q_j)$, correspondingly. These calculations are carried out once.

Further the transformation matrix connecting SC C_1 and C_P is defined. For receiving this matrix it is necessary to carry out consistently rotations on angle $(-\pi/2)$ about axes of z_p and x_p. It is also necessary to consider shift of SC C_1 along l_1 link. As a result this matrix can be represented in the form:

$$A_P^1 = R_{Z90} \cdot R_{X90} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & -l_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & -l_1 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{1}$$

Stage 2. Numerical values of elements of the vector R_p in the SC C_p are determined on this stage according to known values of elements of vector r_p.

$$R_P = R_{Z1} \cdot \left(A_P^1 \cdot r_P\right) = \begin{pmatrix} c_1 & s_1 & 0 & 0 \\ -s_1 & c_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \left(\begin{pmatrix} 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & -l_1 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 0 \\ l_2 \cdot c_2 + l_3 \cdot c_{2,3} \\ l_2 \cdot s_2 + l_3 \cdot s_{2,3} \\ 1 \end{pmatrix} \right) = \begin{pmatrix} c_1 \cdot (l_2 \cdot s_2 + l_3 \cdot s_{2,3}) \\ -s_1 \cdot (l_2 \cdot s_2 + l_3 \cdot s_{2,3}) \\ -l_1 - l_2 \cdot c_2 - l_3 \cdot c_{2,3} \\ 1 \end{pmatrix}. \tag{2}$$

Stage 3. On this stage the transformation matrix, which connects C_P and C_M, is found. The connection between C_P and C_M (or between C_7 and C_M) depends only on the current orientation of telecamera and $A_7^M = A_M^P$.

As the manipulator and the camera are installed on the mobile bases, it is necessary to consider mutual orientation of systems of coordinates C_K and C_M in general global system of coordinates.

$$A_M^P = R_{Z(M-K)} \cdot R_{Z11} \cdot R_{X12} = \begin{pmatrix} c_{(M-K)} & -s_{(M-K)} & 0 & 0 \\ s_{(M-K)} & c_{(M-K)} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} c_{11} & -s_{11} & 0 & 0 \\ s_{11} & c_{11} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{12} & -s_{12} & 0 \\ 0 & s_{12} & c_{12} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} =$$

$$= \begin{pmatrix} c_{11} \cdot c_{(M-K)} - s_{11} \cdot s_{(M-K)} & -c_{12} \cdot (c_{11} \cdot s_{(M-K)} + s_{11} \cdot c_{(M-K)}) & s_{12} \cdot (c_{11} \cdot s_{(M-K)} + s_{11} \cdot c_{(M-K)}) & 0 \\ c_{11} \cdot s_{(M-K)} + s_{11} \cdot c_{(M-K)} & c_{12} \cdot (c_{11} \cdot c_{(M-K)} - s_{11} \cdot s_{(M-K)}) & -s_{12} \cdot (c_{11} \cdot c_{(M-K)} - s_{11} \cdot s_{(M-K)}) & 0 \\ 0 & s_{12} & c_{12} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}. \tag{3}$$

Stage 4. The inverse task of kinematics (ITK) of the manipulator is solved. The numerical values of elements of the vector $R_C = A_M^P \cdot R_P$ in C_M (i.e. new position of manipulator grip) are determined at current time.

The coordinate q_6 can be calculated using the equation

$$q_6 = arctg(y_M / x_M). \tag{4}$$

Using vector R_C elements the values of vector $r_C = R_C \cdot R_{Z6}$ elements are calculated.

The numerical values of the generalized coordinates of manipulator transferred degrees of freedom q_7, q_8 are determined on the basis of the received values of elements of a vector r_c. These coordinates are the setting signals for drives of these degrees of freedom.

It is necessary to note, that a vector r_c with length l and links l_5, l_6 of the manipulator form a triangle (see Fig. 2). Value l is calculated by equation: $l = \sqrt{x_4^2 + y_4^2 + z_4^2}$, where x_4, y_4, z_4 - coordinates of a vector r_c .

The area of this triangle is determined using the equation:

$$S = 1/2lh_1 = 1/2l_5h = \sqrt{p(p-l_5)(p-l_6)(p-l)}\,, \tag{5}$$

where $p = 0.5 \cdot (l_5 + l_6 + l)$ - half of triangle perimeter, h_1, h_2 - its heights.

Values of h_1, h_2 are determined from these equations:

$$h_1 = 2\sqrt{p(p-l_5)(p-l_6)(p-l)}\,/\,l\,,$$
$$h_2 = 2\sqrt{p(p-l_1)(p-l_2)(p-l)}\,/\,l_5\,. \tag{6}$$

On the other hand from Fig. 2 it is evidently: $h_1 = l_5 \sin\alpha$, $h_2 = l_6 \sin q_8$. Further it is possible to determine $q_8 = \arcsin(h_2/l_6) = \arcsin(2\sqrt{p(p-l_5)(p-l_6)(p-l)}\,/\,l_5l_6)$.

The coordinate q_7 (see Fig. 2) can be calculated using the equation:

$$q_7 = 90 - (\alpha + \beta) = 90 - (\arcsin(\frac{h_1}{l_5}) + \arcsin(\frac{z_4}{l})) = 90 - (\arcsin(\frac{2\sqrt{p(p-l_5)(p-l_6)(p-l)}}{l_5 l}) + \arcsin(\frac{z_4}{l})). \tag{7}$$

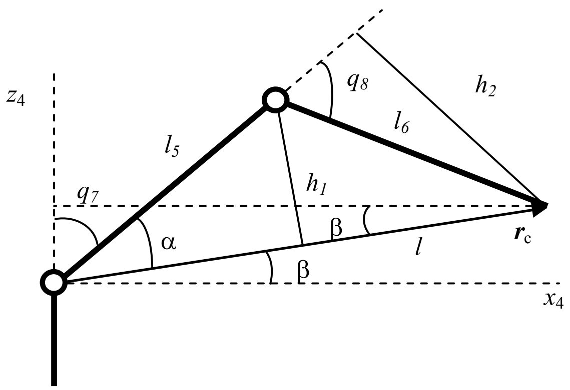

Fig. 2. The scheme for decision ITK of manipulator.

The constructive limitations in degrees of freedom of manipulator exclude an opportunity of occurrence of ambiguity at calculation of inverse trigonometric functions when ITK is solve. For this purpose limiting values q_i were accepted equal $\pi/2$.

Stage 5. On this stage the formation of signals which control orientation of manipulator grip is began. For realization of this regime the transformation from SC C_3 to SC C_2 is carrying out using the matrix A_3^2 , i.e. the current orientation of SD handle in SC is described. For obtaining the matrix A_3^2 the system of coordinates C_3 must be consecutively turned at angles q_5, q_4 about to corresponding axes y_2 and x_2:

$$A_3^2 = R_{X4} \cdot R_{Y5} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c_4 & -s_4 & 0 \\ 0 & s_4 & c_4 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_5 & 0 & s_5 & 0 \\ 0 & 1 & 0 & 0 \\ -s_5 & 0 & c_5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_5 & 0 & s_5 & 0 \\ s_4 \cdot s_5 & c_4 & -s_4 \cdot c_5 & 0 \\ -c_4 \cdot s_5 & s_4 & c_4 \cdot c_5 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (8)$$

Orientation of manipulator grip is described by a matrix A_6^5. The current orientation of the image of manipulator grip on the screen of telemonitor must coincide with the current orientation of SD handle. As result $A_6^5 = A_3^2$. On the other hand the matrix A_6^5 can be represented in the form:

$$A_6^5 = R_{Y9} \cdot R_{Z10} = \begin{bmatrix} c_9 & 0 & s_9 & 0 \\ 0 & 1 & 0 & 0 \\ -s_9 & 0 & c_9 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_{10} & -s_{10} & 0 & 0 \\ s_{10} & c_{10} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_9 \cdot c_{10} & -c_9 \cdot s_{10} & s_9 & 0 \\ s_{10} & c_{10} & 0 & 0 \\ -s_9 \cdot c_{10} & s_9 \cdot s_{10} & c_9 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (9)$$

In result as all elements of a matrix A_6^5 are calculated it is possible to determine all generalized coordinates of orienting degrees of freedom of manipulator: $q_9 = \arccos(a_{33})$, $q_{10} = \arccos(a_{22})$, where $a_{i,j}$ are numerical values of corresponding elements of the matrix A_6^5.

In former algorithm the ambiguity appears when inverse trigonometric functions are calculated. For its elimination it is necessary to limit values of generalized coordinates in a range $(0, \pi]$.

The generalized coordinates, which are calculated at stages 4 and 5, are the setting signals for drives of all degrees of freedom of manipulator.

4. Simulation and experiment results

For checking efficiency of the proposed algorithm of semiautomatic control the simulation of system work was carried out. It was assumed that $l_1 = 0.1$ m; $l_2 = 0.135$ m; $l_3 = 0.14$ m; $l_4 = 0.21$ m; $l_5 = 0.25$ m; $l_6 = 0.2$ m; coordinates q_i $(i = 1, 5, 6, 10, 11)$ have ranges of change $[-\pi/2, \pi/2]$; coordinates q_i $(i = \overline{2,4}, \overline{7,9}, 12)$ - a range $[0, \pi/2]$. The laws of variation of generalized coordinates of SD in the time have forms: $q_1 = (\pi/6)\sin 0.7t$, $q_2 = (\pi/8)\sin(0.5t + 0.9)$, $q_3 = (\pi/8)\sin(0.7t + 0.8)$, $q_4 = (\pi/6)\sin(0.5t + 0.9)$, $q_5 = (\pi/6)\sin 0.5t$.

On Fig. 3-4 the results of the simulation of system work with the turned telecamera (when $q_{11} = \pi/6$ and $q_{12} = 0$) are shown. From Fig. 3 it is evident that coordinates of vectors of $r_p = (x_1, y_1, z_1, 1)$ and $r_c = (x_4, y_4, z_4, 1)$ don't coincide because of the manipulator and the setting device have different physical sizes and orientation. From Fig. 4 it is evident that the generalized coordinates of SD and manipulator don't coincide too. But thus the manipulator completely repeats all motions of the setting device taking into account orientation of television camera. It should be noted that before switching on the mode of tracking it is necessary to coordinate an initial configuration of the manipulator on the screen of the monitor and the SD configuration. As telecamera is turned, in this case the manipulator must be turned in the joint q_6 at same angle $q_{11} = \pi/6$ (see Fig. 4). Further the generalized coordinates of manipulator repeat the laws of SD motion taking into account an initial mismatch and orientation of telecamera.

For better check of efficiency of the offered algorithm it is desirable to carry out mathematical modeling of work of system with use of the data received from real physical object. As an experimental platform we use the four-wheel mobile transport robot. The specified robot is equipped with the sensors of an angle of rotation measuring an angle of rotation of a platform in global system of coordinates. On such mobile basis the manipulator and a television camera may be installed. Figure 5 shows results of these experiments.

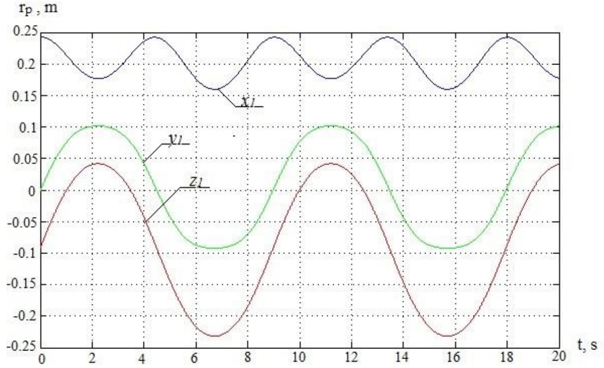

Fig. 3. Coordinates of vectors r_p and r_c when $q_{11} = \pi / 6,\ q_{12} = 0$.

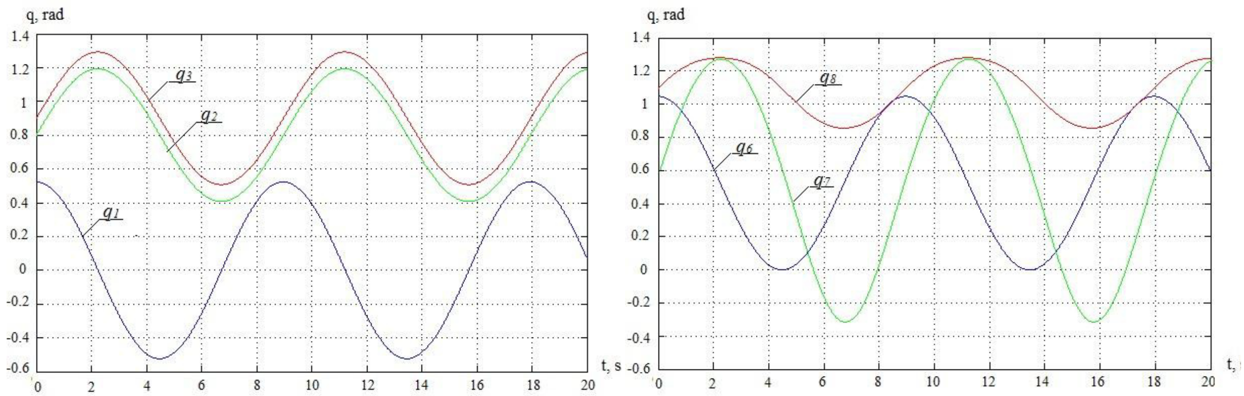

Fig. 4. Generalized coordinates q_1 , q_2 , q_3 and q_6 , q_7 , q_8 when $q_{11} = \pi / 6,\ q_{12} = 0$.

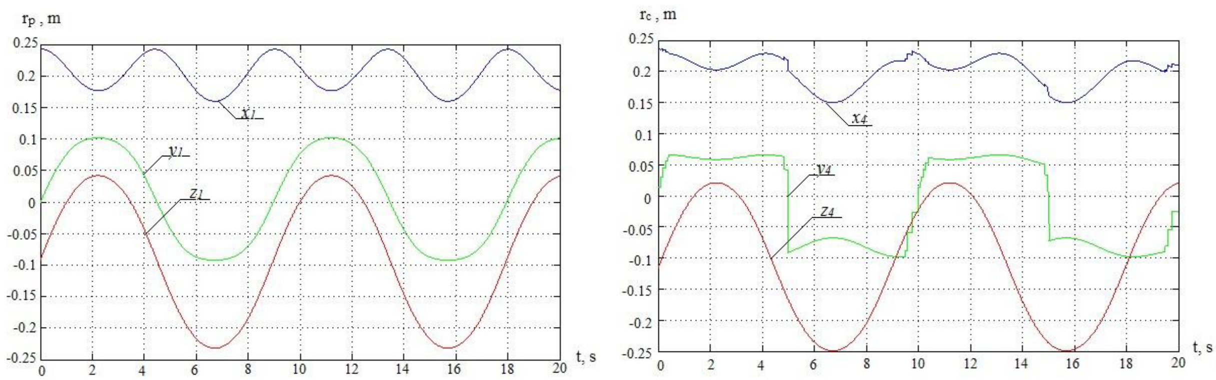

Fig. 5. Coordinates of vectors r_p and r_c when q_M and q_K changed.

From Fig. 5 it is visible that the changing of an angle of rotation of the mobile robot leads to change of coordinates of a vector $r_c = (x_4, y_4, z_4, 1)$. At such orientation of a television camera the coordinate z_4 didn't change (coincided with z_1), but coordinates x_4, y_4 changed. During experiment the manipulator completely repeats all motions of the setting device taking into account orientation of television camera and mobile basis.

Conclusion

The system of semiautomatic position telecontrol by the multilink manipulator installed on the mobile basis is proposed. This system can be applied for the robotic complexes intended for remote work in hard-to-reach and dangerous for the person places. The proposed method of semiautomatic telecontrol by the multilink manipulator allows to consider automatically spatial orientation of an optical axis of a telecamera during execution by this manipulator of various technological operations. In this case the psychological load on operator is reduced because operator doesn't need to constantly consider the current orientation of telecamera, manipulator and SD. The operator always has a possibility to select the convenient orientation of telecamera and position of SD handle. As result the system of telecontrol allows to improve operational characteristics and to expand functionality of a mobile robotic complex. It provides opportunity to receive continuous visual information from working zone in several views, to increase efficiency of use and service life of the mobile robot at its use in zones of high risk. Results of the executed mathematical modeling completely confirmed working capacity and high efficiency of the offered approach to creation of the semiautomatic system of telecontrol by the multilink manipulator. Engineering realization of proposed telecontrol system doesn't cause principle difficulties because in this case it is necessary to execute some additional mathematical calculations only.

Acknowledgements

The paper is supported by Russian Ministry of Education and Science (Agreement № 14.604.21.0054) and Russian Foundation of Basic Research (Grant № 13-08-01344).

References

[1] Changhwan C., Yongchil S., Seungho J., Seungho K. Tele-Operated Fuel Handling Machine Manipulation Robot for the Nuclear Power Plants. Proc. CD-ROM of the 6th Asian Control Conf. Bali, Indonesia, 2006, pp. 983-987.

[2] Andreev V.P., Pryanichnikov V.E. Operation Environment of Mobile Robots with Supervision Control, Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium, Volume 22, No. 1, Vienna, Austria, 2011, pp. 0021-0022.

[3] D. Hwang, Teleoperation performance with a kinematically redundant slave robot, Ph.D. Dissertation, University of Washington, Department of Electrical Engineering.

[4] Cetin L., Baser O., Keskin O., Uyar E. Vision Based Control Algorithm for a Mobile Manipulator Annals of DAAAM for 2011 & Proceedings of the 22nd International DAAAM Symposium, Volume 22, No. 1, Vienna, Austria, 2011, pp. 0449-0450.

[5] Lee D., Spong M.W. Passive bilateral control of teleoperators under constant time-delay, Proc.16 IFAC World Congress. Prague, Czech Rep., File 03009.pdf (CD-ROM), 2005, pp.1- 6.

[6] Tarca R., Pasc I., Tarca N., Popentiu-Vladicescu F. Remote robot control Via Internet Using Augmented Reality, Proc. of the 18th DAAAM Int. Symp. Intelligent Manufacturing & Automation, Zadar, Croatia, 2007, pp. 739-740.

[7] Vladimir Filaretov, Alexey Katsurin. Method of Semiautomatic Combined Control by Manipulator Using Mobile Telecamera. Proc. of 11th International Conference on Control, Automation and Systems (ICCAS 2011). KINTEX, Gyeonggi-do, Korea, 2011, pp. 649-654.

[8] Tomasz Kosicki and Trygve Thomessen. Cognitive Human-Machine Interface Applied in Remote Support for Industrial Robot Systems. International Journal of Advanced Robotic Systems, Vol. 10, 342, 2013. pp. 1-11.

[9] Soichiro Suzuki, Satoshi Hasegawa and Masayuki Okugawa. Remote control system of disaster response robot with passive sub-crawlers considering falling down avoidance. ROBOMECH Journal, Vol. 1, 20, 2014, pp. 1-12.

[10] Filaretov Vladimir, Katsurin Alexey. Method of Semiautomatic Position Control by Manipulator Using Telecamera Which Changes Its Orientation. Advanced Materials Research, Vol. 717, 2013, pp. 573-578.

[11] Angeles, J. Fundamentals of Robotic Mechanical Systems: Theory, Methods, and Algorithms, 3rd Edition, SpringerVerlag, ISBN-10: 0387945407, New York, 2006.

[12] Craig, JJ. Introduction to Robotics –Mechanics and Control, 3rd ed., Pearson Education, Inc., 2005.

[13] Kurfess, TR. Robotics and automation handbook, CRC press., 2005.