Evaluation of Parameters of Transactions When Remote Robot Control

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Abstract. It is shown that control of mobile robots is implemented on strategic, tactic and functional-logic levels. A strategy of mobile robot behavior is defined by human operator, being functioning in dialogue with dialogue computer. Tactic and functional robotic levels are realized by onboard computer. Human operator, dialogue and onboard computers are the subjects of control, who exchange data, volumes and content of which define characteristics of control. Data are transmitted, when a transaction between subjects occurs. So, working out the model of transactions and evaluation its parameters is the actual problem. The model of generator of transactions from human operator and mobile robot onboard computer to dialogue computer, and vice versa from dialogue computer to the human operator and onboard computer is worked out. It is shown that due to transactions in operators of algorithms competition process is developed. Such a process defines a value of parameters of flows of transactions. Formulae for the primary evaluation of parameters are obtained. Iteration procedure for elaboration of parameters of flows of transactions is worked our.

Keywords: Mobile robot · Control · Transaction · Flow · Function-logic level · Dialogue · Semi-markov process · “Competition” · Iteration

1 Introduction

Mobile robots (PR) at present are rather widely used at monitoring of environment [1], in industry [2,3] and other spheres of mankind activity [4–6]. Main feature of contemporary mobile robotics consists in a lack of hard/software intelligence. Due to the fact strategic functions of control, human operator pared with dialogue computer is executed. Tactic and functional-logic levels are realized in the robot control system itself. On such levels onboard computer receives from dialogue computer flow of commands, interpret them, and actuates onboard equipment control loops. So, main feature of tasks of such a level are rigid requirements to a lag of reactions of control system onto both external commands and sensors state. Second feature is the necessity of time coordination of

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operation of onboard equipment, receiving commands, forming and dispatching messages to human, etc.

So evaluation time factor of dialogue regimes of control is the actual and at present non-solved problem.

2 Common Model of Control

Principle of mobile robot control is shown on Fig. 1 [7–9].

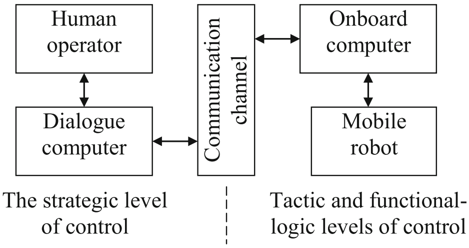

Fig. 1. Principle of mobile robot remote control

MR on the strategic level is managed by human operator, being situated at remote point of control, and maintaining an interactive dialogue with dialogue computer. Dialogue computer through communication channel is linked with onboard computer. In onboard computer external commands are interpreted, and both tactic and functional-logic levels of control are realized. Realization of command causes changes of onboard equipment states. Feedback information through onboard computer, communication channel and dialogue computer is transmitted to human opera-tor for making decision on the further continuation of control process.

In the functional diagram one can distinguish three active subjects, which operate, each on its own algorithm: human operator, dialogue computer and onboard computer. Mobile robot itself is the passive control object. As a result of control process, every subject generates transactions to the adjacent subject.

For evaluation of parameters of flows of transactions analytical model of such a system should be worked out. With taking into account features of algorithms under consideration (cyclic recurrence, quasi-stochastic nature of switches to adjacent operators, quasi-accidental time of interpretation of operators) [10] model of it is the ergodic semi-Markov process [11]. Operators of algorithm may be considered ad states of the process. Interpretation of algorithm may be considered as random wandering through the states of semi-Markov process.

In common semi-Markov process, which describe generators of transactions are as follows [10,11]:

$$ {}^{i}\mu = \left\{ {}^{i}A, {}^{i}\boldsymbol{h}(t) \right\}, i = 1, 2, 3, \tag{1} $$

where ${}^{1}\mu$ – is the process, describing the human-operator; ${}^{2}\mu$ and ${}^{3}\mu$ – are processes, describing dialogue and onboard computers correspondingly; ${}^{i}A$ – is the set of states; ${}^{i}\boldsymbol{h}(t) = [h_{m_i n_i}(t)]$ – is the semi-Markov matrix of size $J_i \times J_i$; t – is the time;

$${}^{i}A = \begin{cases} \{a_{1_i}, \ldots, a_{s_i}, \ldots, a_{S_i}, a_{S_i+1}, \ldots, a_{j_i}, \ldots, a_{J_i}\}, & \text{when } i = 1, 2; \\ \{a_{1_i}, \ldots, a_{s_i}, \ldots, a_{U_i}, a_{U_i+1}, \ldots, a_{S_i}, a_{S_{i+1}}, \ldots, a_{j_i}, \ldots, a_{J_i}\}, & \text{when } i = 3. \end{cases} \quad (2)$$

$$h_{m_i n_i}(t) = p_{m_i n_i} f_{m_i n_i}(t); \quad (3)$$

$p_{m_i n_i}$ –is the probability of switching from state $a_{m_i} \in^i A$ to state $a_{n_i} \in^i A$; $f_{m_i n_i}(t)$ – is density of time of residence in state $a_{m_i} \in^i A$ on condition of further switching to $a_{n_i} \in^i A$;

$$\sum_{n_i=1}^{J_i} p_{m_i n_i} = 1. \quad (4)$$

Nodes of graph with numbers from 1_i till S_i are analogues of states of transactions generation. In semi-Markov process, describing dialogue computer, nodes $A_{U_3} = \{a_{1_3}, \ldots, a_{u_3}, \ldots, a_{U_3}\}$ are analogue of states of generation of transactions from dialogue computer to human operator. Nodes $A_{S_3} = \{a_{U_3+1}, \ldots, a_{s_3}, \ldots, a_{S_3}\}$ are analogue of states of generation of transactions from dialogue to onboard computers. Nodes $A_{J_i} = \{a_{S_i+1}, \ldots, a_{j_i}, \ldots, a_{J_i}\}$ are analogue of other states of semi-Markov processes.

Transactions are generated in one of two cases:

1. When direct switching from states with numbers from 1_i till S_i to states with numbers from 1_i till S_i occurs;
2. When switching from states with numbers from 1_i till S_i to states with numbers from $S_i + 1_i$ till J_i with further wandering till states from 1_i till S_i occurs.

With use of methods described in [12, 13], Semi-Markov processes may be reduced to processes, included generation transaction state only:

$${}^{i}\mu \rightarrow^{i} \mu' = \left\{{}^{i}A', {}^{i}\boldsymbol{h}'(t)\right\}, i = 1, 2, 3, \quad (5)$$

where ${}^{i}A'$ – is reduced set of states; ${}^{i}\boldsymbol{h}'(t)$ – is semi-Markov matrix of size $S_i \times S_i$;

$${}^{i}A' = \begin{cases} \{a_{1_i}, \ldots, a'_{1_i}, \ldots, a'_{s_i}, \ldots, a'_{S_i}\}, & \text{when } i = 1, 2; \\ \{a_{1_i}, \ldots, a'_{1_i}, \ldots, a'_{u_i}, \ldots, a'_{U_i}, a'_{U_i+1}, \ldots, a'_{s_i}, \ldots, a'_{S_i}\}, & \text{when } i = 3. \end{cases} \quad (6)$$

$${}^{i}\boldsymbol{h}'(t) = \left[h'_{m_i n_i}(t)\right]. \quad (7)$$

At each switching of semi-Markov process (5) one transaction is generated. Due to the fact, that transformations applied are equivalent ones, processes (5) are ergodic too. For external observer probabilities of residence in states of ergodic semi-Markov process in steady regime of switching, are defined as follows:

$$\pi_{m_i} = \frac{T_{m_i}}{\tau_{m_i}} \tag{8}$$

where T_{m_i} – is the expectation of time of residence of ergodic semi-Markov process (1) in the state $a'_{m_i} \in^i A'$; τ_{m_i} – is the tine of return into state $a'_{m_i} \in^i A'$.

Time of residence in state $a'_{m_i} \in^i A'$ is as follows

$$T_{m_i} = \int_0^\infty t \sum_{m_i=1_i}^{S_i} h'_{m_i n_i}(t)dt. \tag{9}$$

For evaluation of time τ_{m_i} one should to split the state a'_{m_i} of semi-Markov process (1) to ${}^b a'_{m_i}$ and ${}^e a'_{m_i}$. This leads to the transformation of matrix $\boldsymbol{h}'_i(t)$ as follows:

- column with number m_i should be transmitted to column with number S_i+1;
- column with number m_i and row with number S_i+1 should be fulfilled with zeros.

Matrix $\tilde{\boldsymbol{h}}'(t)$ after transformation is of size $(S_i+1)\times(S_i+1)$. Expectation of time of return is as follows:

$$\tau_{m_i} = \int_0^\infty t L^{-1r} \boldsymbol{I}_{S_i+1} \sum_{k=1}^\infty \left\{ L\left[\tilde{\boldsymbol{h}}'(t)\right]\right\}^k {}^c\boldsymbol{I}_{m_i} dt, \tag{10}$$

where ${}^c\boldsymbol{I}_{m_i}$ – is the column vector of size S_i+1, m_i-th element of which is equal to one, and other elements are zeros; ${}^r\boldsymbol{I}_{m_i}$ – is row vector of size S_i+1, S_i+1-th element of which is equal to one, and other elements are zeros; $L[\ldots], L^{-1}[\ldots]$ - are direct and inverse Laplace transforms correspondingly.

Due to (8) and property of ergodics of semi-Markov process under investigation, densities of time between neighboring transactions are as follows:

$$g_i(t) = \sum_{m_i=1_i}^{S_i} \pi_{m_i} \sum_{n_i=1_i}^{S_i} h'_{m_i n_i}(t), \qquad T_i = \int_0^T t g_i(t)dt,$$
$$D_i = \int_0^T (t-T_i)^2 g_i(t)dt, \qquad i=1,2, \tag{11}$$

where $g_i(t), T_i, D_i$ – are density, expectation and dispersion of time between transactions, correspondingly.

In such a way, processes ${}^1\mu'$ and ${}^2\mu'$ generate one stream each to adjacent process ${}^3\mu'$. Semi-Markov processes of generators after reduction are as follows:

$$ {}^{i}\gamma = \{\{{}^{i}\alpha\}, [g_i(t)]\}, i = 1, 2. \tag{12} $$

Semi-Markov process ${}^{3}\mu'$ born two flows of transactions: to the process ${}^{1}\mu'$ and to the process ${}^{2}\mu'$. Probabilities of residence ${}^{3}\mu'$ in the state of generation transactions to ${}^{1}\mu'$ and ${}^{2}\mu'$ for the external observer are as follows:

$$ \pi_{31} = \sum_{m_3=1_3}^{U_3} \pi_{m_3}; \qquad \pi_{32} = \sum_{m_3=U_3+1}^{S_3} \pi_{m_3}, \tag{13} $$

where π_{31} – is the probability of residence of ${}^{3}\mu'$ in the state of generation of trans-actions from ${}^{3}\mu'$ to ${}^{1}\mu'$; π_{32} – is the probability of residence of in the state of generation of transactions from ${}^{3}\mu'$ to ${}^{2}\mu'$.

Thus semi-Markov process of generation of transactions both from ${}^{3}\mu'$ to ${}^{1}\mu'$ and ${}^{2}\mu'$ is as follows

$$ {}^{3}\gamma = \left\{ \left\{ {}^{3}\alpha_0, {}^{3}\alpha_1, {}^{3}\alpha_2 \right\}, \begin{bmatrix} 0 & \delta(t)\pi_U & \delta(t)\pi_S \\ f_U(t) & 0 & 0 \\ f_S(t) & 0 & 0 \end{bmatrix} \right\} \tag{14} $$

where ${}^{3}\alpha = \left\{ {}^{3}\alpha_0, {}^{3}\alpha_1, {}^{3}\alpha_2 \right\}$ – is set of states, when switching from which transaction to ${}^{1}\gamma$ is generated; ${}^{3}\alpha_0$ – is the state, which define probability of the next switching; $\delta(t)$ – is the Diraq δ-function;

$$ \pi_U = \sum_{m_3=1_3}^{U_3} \pi_{m_3}; \qquad \pi_S = \sum_{m_3=U_3+1}^{S_3} \pi_{m_3}, \tag{15} $$

$$ f_U(t) = \frac{\sum\limits_{m_3=1_3}^{U_3} \pi_{m_3} \sum\limits_{n_3=1_3}^{S_3} h'_{m_3 n_3}(t)}{\sum\limits_{m_3=1_3}^{U_3} \pi_{m_3}}; $$

$$ f_S(t) = \frac{\sum\limits_{m_3=U_3+1}^{S_3} \pi_{m_3} \sum\limits_{n_3=1_3}^{S_3} h'_{m_3 n_3}(t)}{\sum\limits_{m_3=U_3+1}^{S_3} \pi_{m_3}}. \tag{16} $$

For evaluation of density of time between transactions from ${}^{3}\gamma$ to ${}^{1}\gamma$ one should to split the state ${}^{3}\alpha_1$ onto ${}^{3b}\alpha_1$ and ${}^{3e}\alpha_1$. Semi-Markov process ${}^{3}\gamma$ with divided state ${}^{3}\alpha_1$ is as follows:

$$ {}^{3}\gamma_1 = \left\{ \left\{ \alpha_1, {}^{3b}\alpha_1, {}^{3}\alpha_2, {}^{3e}\alpha_1 \right\}, \begin{bmatrix} 0 & 0 & \delta(t)\pi_S & \delta(t)\pi_U \\ f_U(t) & 0 & 0 & 0 \\ f_S(t) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \right\}. \tag{17} $$

Density of time between transactions from ${}^3\gamma$ to ${}^1\gamma$ is equal to:

$$g_{31}(t) = L^{-1}\left[(0,1,0,0)\,,\sum_{k=1}^{\infty}\left\{L\begin{bmatrix} 0 & 0 & \delta(t)\pi_S & \delta(t)\pi_U \\ f_U(t) & 0 & 0 & 0 \\ f_S(t) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\right\}^k \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}\right]. \quad (18)$$

Correspondingly, semi-Markov process ${}^3\gamma$ with divided state ${}^3\alpha_2$ and density of time between transactions from ${}^3\gamma$ to ${}^2\gamma$ are as follows:

$${}^3\gamma_1 = \left\{\left\{\alpha_1,{}^3\alpha_1,{}^{3b}\alpha_2,{}^{3e}\alpha_2\right\},\begin{bmatrix} 0 & \delta(t)\pi_U & 0 & \delta(t)\pi_S \\ f_U(t) & 0 & 0 & 0 \\ f_S(t) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\right\}; \quad (19)$$

$$g_{32}(t) = L^{-1}\left[(0,0,1,0)\,,\sum_{k=1}^{\infty}\left\{L\begin{bmatrix} 0 & \delta(t)\pi_U & 0 & \delta(t)\pi_S \\ f_U(t) & 0 & 0 & 0 \\ f_S(t) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\right\}^k \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}\right]. \quad (20)$$

Due to the fact, that transactions are generated as a result of random wandering through the states of semi-Markov processes, train of transactions, being generated when moving through every separate trajectory, may be considered as independent flow. So, united train of transactions may be considered as combination of transactions. In accordance theorem by Grigelionis B. [14] this united flow is a Poisson one. This is why next restrictions to densities of time between transactions may be accepted:

$$g_i(t) = \lambda_i \exp(-\lambda_i t); \quad (21)$$

$$g_{3j}(t) = \lambda_{3j} \exp(-\lambda_{3j} t); \quad (22)$$

where $\lambda_i, \lambda_{3j}, i, j = 1, 2$ – are the densities of flows of transactions

$$\lambda_i = \frac{1}{T_i}; \qquad \lambda_{3j} = \frac{1}{\int_0^\infty t g_{3j}(t)dt}. \quad (23)$$

So processes ${}^1\gamma, {}^2\gamma, {}^3\gamma$ may be considered as the Markov processes with continual time.

3 "Competition" of Transactions

As it follows from models above, switching in every process ${}^1\gamma, {}^2\gamma, {}^3\gamma$ lead to generation a transaction into adjacent Markov process. When transaction comes restart of corresponding Markov process takes place. When restarting, transaction is not generated. In such a way in the states ${}^i\alpha, i = 1, 2, {}^3\alpha_1, {}^3\alpha_2$

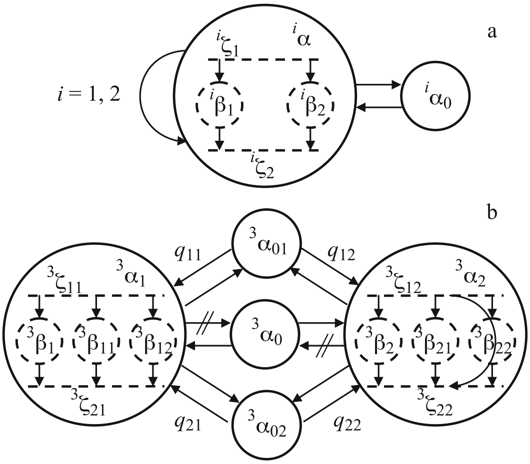

Fig. 2. "Competition" of transactions

"competitions" are evolved (Fig. 2a, b) [15,16]. Models of "competition", as fragments of Petri-Markov nets [17] are shown with dash lines within states $^i\alpha, i = 1, 2, ^3\alpha_1, ^3\alpha_2$ of processes $^1\gamma, ^2\gamma, ^3\gamma$ on Fig. 2a, b.

Into models additional states $^i\alpha_0, i = 1, 2, ^3\alpha_{01}, ^3\alpha_{02}$ are inserted for simulation of restart processes. After restarting of the processes $^1\gamma, ^2\gamma$, unconditional switching to state $^i\alpha, i = 1, 2$ takes place (Fig. 2a). Process $^3\gamma$ switches into states $^3\alpha_1, ^3\alpha_2$, with probabilities q_{11}, q_{12}, if transaction comes from $^1\gamma$, and with probabilities q_{21}, q_{22}, if transaction comes from $^2\gamma$ (Fig. 2b).

Petri-Markov net, evolved in state $^i\alpha$, has places $^i\beta_1, ^i\beta_2$, and transitions $^i\zeta_1, ^i\zeta_2, i = 1, 2$. Places simulate next processes: residence in state $^i\alpha$ with full-time completion and residence in state $^i\alpha$ till interrupt delivery from $^3\gamma$. Transitions $^i\zeta_1, ^i\zeta_2, i = 1, 2$ simulate start and finish of "competition", correspondingly.

Petri-Markov nets, evolved in states $^3\alpha_j, j = 1, 2$, have places $^3\beta_i, ^3\beta_{j1}, ^3\beta_{j2}, i = 1, 2$, and transitions $^3\zeta_{ij}, i, j = 1, 2$. Places simulate next processes: $^3\beta_j$ – residence in states $^3\alpha_j, j = 1, 2$ with full-time completion; $^3\beta_{ij}$ – residence transactions from $^i\gamma_i, i, j = 1, 2$. Transitions simulate $^3\beta_{1j}$ – start, $^3\beta_{2j}$ – finish of "concurrency".

Switching from transitions $^i\zeta_1, i = 1, 2$, or $^3\zeta_{1j}, j = 1, 2$ is executed simultaneously. "Winner" of "competition" is the place, which switches to the transition $^i\zeta_2, i = 1, 2$, or $^3\zeta_{2j}, j = 1, 2$ the first.

Taking into account (21), (22) density of at least one switch to $^i\zeta_2$, is as follows (15)

$$^i f_\zeta(t) = \lambda_i \exp\left[-t\left(\lambda_i + \lambda_{3i}\right)\right] + \lambda_{3i} \exp\left[-t\left(\lambda_i + \lambda_{3i}\right)\right], i = 1, 2. \quad (24)$$

Densities of time of switches to $^i\zeta_2$, whatever the outcome of the "competition", are quite equal and as follows

$$^i f_{i\zeta}(t) = ^i f_{3i\zeta}(t) = \left(\lambda_i + \lambda_{3i}\right) \exp\left[-t\left(\lambda_i + \lambda_{3i}\right)\right], i = 1, 2. \quad (25)$$

Probabilities of "winning" in "competition" will be the next:

$$\begin{pmatrix} {}^{i}p_{i\zeta} \\ {}^{i}p_{3i\zeta} \end{pmatrix} = \frac{1}{\lambda_{3i}+\lambda_i}\begin{pmatrix} \lambda_i \\ \lambda_{3i} \end{pmatrix}, i = 1, 2, \tag{26}$$

where ${}^{i}p_{i\zeta}$ and ${}^{i}f_{i\zeta(t)}$ – are a probability and density of time of "winning" in "competition" the place ${}^{i}\beta_1$, accompanied with generation of the transaction to ${}^{3}\gamma$; ${}^{i}p_{3i\zeta}$ and ${}^{i}f_{3i\zeta(t)}$ – are a probability and density of time of "winning" in "competition" the place ${}^{i}\beta_2$, linked with receiving transaction from ${}^{3}\gamma$.

Taking into account (21), (22) density of at least one switch to ${}^{3}\zeta_{2j}, j = 1, 2$, is as follows (15)

$$f_{\gamma j}(t) = \lambda_{3j}\exp\lfloor -t\left(\lambda_{3j}+\lambda_1+\lambda_2\right)\rfloor + \lambda_1\exp\lfloor -t\left(\lambda_{3j}+\lambda_1+\lambda_2\right)\rfloor + \\ +\lambda_2\exp\lfloor -t\left(\lambda_{3j}+\lambda_1+\lambda_2\right)\rfloor. \tag{27}$$

Densities of time of switches to ${}^{3}\zeta_{2j}$, whatever the outcome of the "competition", are quite equal and as follows

$${}^{3}f_{3\zeta j}(t) ={}^{3} f_{1\zeta j}(t) ={}^{3} f_{2\zeta j}(t) = \left(\lambda_1+\lambda_2+\lambda_{3i}\right)\exp\left[-t\left(\lambda_1+\lambda_2+\lambda_{3i}\right)\right]. \tag{28}$$

$$\begin{pmatrix} {}^{3}p_{3\zeta j} \\ {}^{3}p_{1\zeta j} \\ {}^{3}p_{2\zeta j} \end{pmatrix} = \frac{1}{\lambda_{3j}+\lambda_1+\lambda_2}\begin{pmatrix} \lambda_{3j} \\ \lambda_1 \\ \lambda_2 \end{pmatrix}, j = 1, 2. \tag{29}$$

4 Iterative Procedure of Correction of Parameters of Flows of Transactions

It is obviously, that transactions, incoming from adjacent Markov processes, change parameters of flows of transactions (21), (22). Subsequent correction of parameters may be obtained with use of iterative procedure. For starting such a procedure one should nominate parameters of (21), (22) as follows:

$$g_i^0(t) = g_i(t); \quad \lambda_i^0 = \lambda_i; \quad g_{3j}^0(t) = g_{3j}(t); \\ \lambda_{3j}^0 = \lambda_{3j}; \quad i, j = 1, 2; \pi_1^0 = \pi_U; \pi_2^0 = \pi_S. \tag{30}$$

Parameters obtained on the l-th step of iteration one should nominate as $g_i^l(t), \lambda_i^l, g_{3j}^l(t), \lambda_{3j}^l$, $i, j = 1, 2; \pi_1^l, \pi_2^l$. Density of time between transactions from ${}^{i}\gamma$, to ${}^{3}\gamma$ is as follows

$$g_i^{l+1}(t) = \lambda_i^{l+1}\exp(-t\lambda_i^{l+1}), i = 1, 2 \tag{31}$$

where

$$\lambda_i^{l+1} = \frac{1}{\int\limits_0^\infty tL^{-1}\lceil(1,0,0)\sum\limits_{k=1}^{\infty}\left\{L\left[{}^{i}\boldsymbol{h}'(t)\right]\right\}^k\begin{pmatrix}0\\0\\1\end{pmatrix}\rceil\, dt}, \tag{32}$$

$$ {}^{i}\boldsymbol{h}^{l}(t)=\begin{pmatrix} 0 & \lambda_i^l \exp\lfloor -t\left(\lambda_i^l+\lambda_{3i}^l\right)\rfloor & \lambda_{3i}^l \exp\lfloor -t\left(\lambda_i^l+\lambda_{3i}^l\right)\rfloor \\ \delta(t) & 0 & 0 \\ \lambda_i \exp\lfloor -t\left(\lambda_i^l+\lambda_{3i}^l\right)\rfloor & 0 & 0 \end{pmatrix} \tag{33} $$

For evaluation parameters of flow of transactions from ${}^{3}\gamma$ to ${}^{1}\gamma$ one should to change the arc $({}^{3}\alpha_1, {}^{3}\alpha_0)$ (marked with dash on Fig. 2b) to arc and absorbing state ${}^{3e}\alpha_1$. In this case set of states of Markov process will be the next: $\left\{{}^{3}\alpha_1, {}^{3}\alpha_2, {}^{3}\alpha_{01}, {}^{3}\alpha_{01}, {}^{3}\alpha_{02}, {}^{3e}\alpha_1\right\}$.

For evaluation parameters of flow of transactions from ${}^{3}\gamma$ to ${}^{2}\gamma$ one should to change the arc $({}^{3}\alpha_2, {}^{3}\alpha_0)$ (marked with double dash on Fig. 2b) to arc and absorbing state ${}^{3e}\alpha_2$. In this case set of states of Markov process will be the next: $\left\{{}^{3}\alpha_1, {}^{3}\alpha_2, {}^{3}\alpha_{01}, {}^{3}\alpha_{01}, {}^{3}\alpha_{02}, {}^{3e}\alpha_2\right\}$.

Values λ_{3j}^{l+1} are as follows

$$ \lambda_{3j}^{l+1}=\frac{1}{\int\limits_0^\infty tL^{-1}\left[{}^{r}\boldsymbol{I}_j \sum\limits_{k=1}^{\infty}\left\{L\left[{}^{3}_{j}\boldsymbol{h}^{l}(t)\right]\right\}^k {}^{c}\boldsymbol{I}_6\right]dt}, j=1,2 \tag{34} $$

where ${}^{3}_{j}\boldsymbol{h}^{l}(t)$ – semi-Markov matrix of size 6×6, j-th column of which is moved to sixth column, j-th column and sixth row are fulfilled with zeros; ${}^{r}\boldsymbol{I}_j$ – is the row vector, j-th element of which is equal to one, and all other elements are equal to zeros; ${}^{r}\boldsymbol{I}_j$ – is the column vector, sixth element of which is equal to one, and all other elements are equal to zeros;

$$ {}^{3}_{1}h_{14}^{l}(t)={}^{3}_{2}h_{14}^{l}(t)=\lambda_1^l \exp\lfloor-\left(\lambda_{31}^l+\lambda_1^l+\lambda_2^l\right)\rfloor; $$

$$ {}^{3}_{1}h_{15}^{l}(t)={}^{3}_{2}h_{15}^{l}(t)=\lambda_2^l \exp\lfloor-\left(\lambda_{31}^l+\lambda_1^l+\lambda_2^l\right)\rfloor; $$

$$ {}^{3}_{1}h_{24}^{l}(t)={}^{3}_{2}h_{24}^{l}(t)=\lambda_1^l \exp\lfloor-\left(\lambda_{32}^l+\lambda_1^l+\lambda_2^l\right)\rfloor; $$

$$ {}^{3}_{1}h_{25}^{l}(t)={}^{3}_{2}h_{25}^{l}(t)=\lambda_2^l \exp\lfloor-\left(\lambda_{32}^l+\lambda_1^l+\lambda_2^l\right)\rfloor; $$

$$ {}^{3}_{1}h_{16}^{l}(t)=\lambda_{31}^l \exp\lfloor-\left(\lambda_{31}^l+\lambda_1^l+\lambda_2^l\right)\rfloor; \quad {}^{3}_{2}h_{26}^{l}(t)=\lambda_{32}^l \exp\lfloor-\left(\lambda_{32}^l+\lambda_1^l+\lambda_2^l\right)\rfloor; $$

$$ {}^{3}_{1}h_{23}^{l}(t)=\lambda_{32}^l \exp\lfloor-\left(\lambda_{32}^l+\lambda_1^l+\lambda_2^l\right)\rfloor; \quad {}^{3}_{2}h_{13}^{l}(t)=\lambda_{31}^l \exp\lfloor-\left(\lambda_{31}^l+\lambda_1^l+\lambda_2^l\right)\rfloor; $$

$$ {}^{3}_{1}h_{31}^{l}={}^{3}_{2}h_{31}^{l}=\pi_1^l\delta(t); \quad {}^{3}_{1}h_{32}^{l}={}^{3}_{2}h_{32}^{l}=\pi_2^l\delta(t); \quad {}^{3}_{1}h_{41}^{l}={}^{3}_{2}h_{41}^{l}=q_{11}\delta(t); $$

$$ {}^{3}_{1}h_{42}^{l}={}^{3}_{2}h_{42}^{l}=q_{12}\delta(t); \quad {}^{3}_{1}h_{51}^{l}={}^{3}_{2}h_{51}^{l}=q_{21}\delta(t); \quad {}^{3}_{1}h_{52}^{l}={}^{3}_{2}h_{52}^{l}=q_{22}\delta(t). $$

Values π_1^{l+1}, π_2^{l+1}, one can define from analysis Markov process ${}^{3}\gamma$ without splitting of states. In steady regime for external observer

$$ \pi_1^{l+1}=\frac{p_{21}\left(\lambda_{32}^l+\lambda_1^l+\lambda_2^l\right)}{p_{21}\left(\lambda_{32}^l+\lambda_1^l+\lambda_2^l\right)+p_{12}\left(\lambda_{31}^l+\lambda_1^l+\lambda_2^l\right)}; $$

$$\pi_2^{l+1} = \frac{p_{12}\left(\lambda_{31}^l + \lambda_1^l + \lambda_2^l\right)}{p_{21}\left(\lambda_{32}^l + \lambda_1^l + \lambda_2^l\right) + p_{12}\left(\lambda_{31}^l + \lambda_1^l + \lambda_2^l\right)}; \tag{35}$$

$$p_{12} = \frac{\lambda_{31}^l \pi_2^l + \lambda_1^l q_{12} + \lambda_2^l q_{22}}{\lambda_{31}^l + \lambda_1^l + \lambda_2^l}; \quad p_{21} = \frac{\lambda_{32}^l \pi_2^l + \lambda_1^l q_{12} + \lambda_2^l q_{22}}{\lambda_{32}^l + \lambda_1^l + \lambda_2^l}. \tag{36}$$

So formulae (30)–(35) describe iteration for correction parameters $\lambda_{31}, \lambda_{32}, \lambda_1, \lambda_2$ of flow of transactions. Procedure may be finished on one of the next criteria;

$$\frac{|\lambda_{31}^l - \lambda_{31}^{l+1}|}{\lambda_{31}^l} < \varepsilon_{31}, \frac{|\lambda_{32}^l - \lambda_{32}^{l+1}|}{\lambda_{32}^l} < \varepsilon_{32}, \frac{|\lambda_1^l - \lambda_1^{l+1}|}{\lambda_1^l} < \varepsilon_1, \frac{|\lambda_2^l - \lambda_2^{l+1}|}{\lambda_2^l} < \varepsilon_2, \tag{37}$$

or on the summing criterion

$$\frac{|\lambda_{31}^l - \lambda_{31}^{l+1}|}{\lambda_{31}^l} + \frac{|\lambda_{32}^l - \lambda_{32}^{l+1}|}{\lambda_{32}^l} + \frac{|\lambda_1^l - \lambda_1^{l+1}|}{\lambda_1^l} + \frac{|\lambda_2^l - \lambda_2^{l+1}|}{\lambda_2^l} < \varepsilon, \tag{38}$$

where $\varepsilon_{31}, \varepsilon_{32}, \varepsilon_1, \varepsilon_2, \varepsilon$ – are some small pre-determined threshold empirically selected.

5 Conclusion

In such a way, the analytical model of remote control of mobile robot is worked out. For construction of such a model both actions of human operator and functioning of dialogue and onboard computer are divided onto sequence of operations for which it is simple to determine time characteristics and probabilities of transfer to other operation. During execution of operations all subjects of process of control generate transactions to adjacent subject. So parameters of transactions were found with the aid of iterative procedure. Result obtained may be also used for working out other dialogue systems, for example for industry ergatic systems control.

Further continuation of investigations in this domain may be directed to an improvement of iteration procedure, to optimization of dialogue algorithms and adaptation it to characteristics of both human operator and mobile robot, to optimization the transaction flows in concrete systems etc.

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