THE CONTROL METHODS FOR SELF-ACTING DEVICES OF THE "ROBOT-MANIPULATOR" TYPE

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Self-acting devices of the robot type are universal automata designed for effective application to a number of profitable tasks with a minimum of human participation. They include the following basic functioning parts: a) a mechanical arm-and-hand manipulator, b) a controlling computer, c) receptors for gathering information on the environment and the inner state of the robot, d) devices providing man-machine cooperation.

Ernst was the first to bring a robot into operation in 1961 /1/.

In 1968 a robot was built and tested at the Leningrad Polytechnic Institute with the cooperation of the Institute of the Oceanology of the Academy of Sciences of the USSR /2, 3/ for the purpose of establishing the possibility of its application in deep water work.

This paper reports on an investigation of a control method for robots which was applied to the deepwater robot in 1968 and to a modified robot in 1971. We think this method shows promise for effective application to a number of profitable tasks. The method which is conditionally called an extremum one /4, 5, 6/ shows promise for a multilevel control structure and allows execution of commands on the basis of only one basic program for each level, the basic computing program.

The method results in the following characteristics features of the commands: first, they are expressed in the natural language (at any rate for the superior levels); second, they ensure the possibility of programming more complex tasks by recombination of programs according to a definite system of rules. The latter circumstance is very important from the point of view of developing a problem-oriented language that may be used in man-machine interaction. It also shows promise for providing further simplification to the cooperation between man and machine.

Basic Principles of Control Organization

According to the extremum method a unit principle which consists in minimization of certain error functions is offered as the basis of control organization at each level. These error functions present the error of the goal-setting command given by the superior level for the value characterizing the current state of the robot and of the environment, which we shall denote as a vector of situation. In this case the goal-setting command is presented by the x_c elements and in the general case by X_c^* subjects of a certain set X belonging to the metrical space. This set which we denote as "space of situation" characterizes the state of the robot and of the environment. Vector of situation is the meaning of some operator P in the same space of situation $x_s = P(v,g)$ where $v \in V \subset R^n$ characterizes the state of the robot and in the simplest case it presents the totality of degrees of freedom of the manipulator and $g \in G$ characterizes the state of environment.

The value of the vector of situation is estimated in the processing of information data gathered by the receptors.

It is suggested that the error functional be expressed as the distance $R(X_c^*, x_s)$ or the square of the distance between the subset X_c^* related to the goal command and the vector of situation x_s where $R(X_c^*, x_s) = \inf R(x_c, x_s)$; $x_c \in X_c^*$.

Control on each level is exercised by forming a minimizing sequence of the functional arguments. These arguments are the goal setting commands for the inferior level and are used in the formation of the functional of this level. The achievement of the minimum of the functional on each level is related to the execution of the command of this level.

Thus the task of control on each level, i.e. the execution of the command, is reduced to the realization of the relevant minimization algorithm of the functional. It is characteristic that the arguments of the functional are constrained due to peculiarities of the environment. They are unknown and are to be found in the process of minimization, i.e. in the process of control realization.

Peculiarities of the Control Levels Organization

The inferior control level is the level which exerts direct influence on the drives affecting the degree of mobility of the manipulator, giving commands to the drives. This level obeys the goal setting commands of the superior level which are brought to giving the value of each coordinate of the degrees of mobility of the manipulator. The goal setting command x_c for this level may be described by n-dimensional vector $x_c = v_c \in V \subset R^n$ whose components express the required values of the coordinates of the degrees of mobility. The situation vector is also n-dimensional vector whose components express current values of the coordinates of the degrees of mobility.

The functional to be minimized is defined by the expression presenting the distance between the vector of situation v_s and the goal setting vector v_c,

$$R(v_c, v_s) = I_O(v) = |v_c - v_s| \qquad (1)$$

where $|v_c - v_s|$ is the norm of the vector difference.

At this level the minimum of the functional is achieved by giving commands to the drives affecting the degrees of mobility which are the output commands of the inferior level. Evidently, the minimization algorithm, i.e. the basic computing program of this level, is to be formed by taking into consideration the dynamic properties of the drives affecting the robot-manipulator. The appropriate algorithms of minimization are reasonable to realize by means of analog devices. They do not differ from the algorithms of control systems discused in the extensive literature on the automatic control and regulation.

The next hierarchical level, called the tactical level gives goal-setting commands v_c to the inferior level. Tactical commands are given by the superior level or by the operator in a language oriented to the problem of robot controlling. The tactical level involves all the possible commands for setting the working tool into a certain spatial position or a multitude of spatial positions alteration of the environment not being necessary at the same time.

The goal setting command is presented as a vector or a subset of vectors, $W^* \subset W \subset R^n$. The components of these vectors are the coordinates of a certain characteristic point of the working tool in the fixed coordinate system, x_1^k, x_2^k, x_3^k (k = 3), (Fig. 1), connected with the body of the robot or to some goal objects of the environment (the first three components). All the rest of the components are the directing cosines or Eiler angles of the mobile coordinate system, x_1^o, x_2^o, x_3^o, of the working tool with respect to the fixed coordinate system.

The situation vector $w_s \in W$ describes the current position of the tool. The functional to be minimized is presented as the square of the distance between the goal-setting command and the situation vector. It is expedient to turn to the argument v of the functional as this is precisely the vector that stipulates for the commands of the inferior level. The minimizing sequence

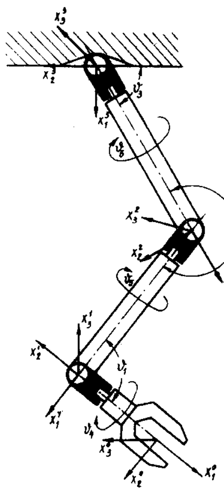


Fig. 1.

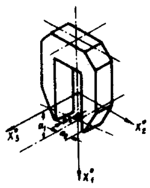


Fig. 2.

of the argument v is the sequence of commands formed by the tactical level for the inferior one, the components of the vector being the coordinates of the degrees of freedom of the arm-and-hand. The transition is exerted with the help of some formulas, the fixed coordinate system of the body of the robot, and the coordinate systems of the arm-and-hand joints. This relation refers to coordinates v_i of the degrees of mobility of the arm-and-hand.

$$x^o = \prod_{j=i}^{j=1} T^t_{j,j-1} x^i - \sum_{j=0}^{j=i-1} f_j l^j \qquad i = 1, 2, \ldots, k \quad (2)$$

$$x^i = \prod_{j=i}^{j=1} T_{j,j-1} (X^o + \sum_{j=0}^{j=i-1} f_j l^j) \qquad i = 1, 2, \ldots, k \quad (3)$$

$$x^k = \prod_{j=k}^{j=i+1} T_{j,j-1} x^i + \sum_{j=1}^{j=k-1} f_j l^j_* \qquad i = 0, 1, \ldots, k-1 \quad (4)$$

$$x^i = \prod_{j=i+1}^{j=k} T^t_{j,j-1} (x^k - \sum_{j=i}^{j=k-1} f_j l^j_*) \qquad i = 0, 1, \ldots, k-1 \quad (5)$$

$$\prod_{j=i}^{j=0} T_{j,j-1} = \begin{bmatrix} l_1^i & l_2^i & l_3^i \\ m_1^i & m_2^i & m_3^i \\ n_1^i & n_2^i & n_3^i \end{bmatrix} \tag{6}$$

$$\prod_{j=i+1}^{j=k+1} T_{j,j-1}^t = \begin{bmatrix} l_{*1}^i & l_{*2}^i & l_{*3}^i \\ m_{*1}^i & m_{*2}^i & m_{*3}^i \\ n_{*1}^i & n_{*2}^i & n_{*3}^i \end{bmatrix} \tag{7}$$

where:

l_j^i, m_j^i, n_j^i $(j=1,2,3)$ are the directing cosines of the i-th coordinate system with respect to the coordinate system of the working tool (the zero coordinate system);

l_j^i, m_j^i, n_j^i $(j=1,2,3)$ are the directing cosines of the i-th coordinate system with respect to the fixed coordinate system;

f_j - is the length of the j-th joint of the arm;

$l^i=(l_1^i,\ l_2^i,\ l_3^i)$; $l_*^i=(l_{*1}^i,\ l_{*2}^i,\ l_{*3}^i)$ are the unit vectors along the axis of symmetry of the i-th joint of the hand as expressed in the zero and fixed coordinate system.

For the most typical arm-and-hand scheme (Fig. 1), the matrices T are identical for all the adjusting joints and are equal to:

$$T_{i,i-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos v_i & \sin v_i \\ 0 & -\sin v_i & \cos v_i \end{bmatrix} \begin{bmatrix} \cos v_{i+k} & 0 & \sin v_{i+k} \\ 0 & 1 & 0 \\ -\sin v_{i+k} & 0 & \cos v_{i+k} \end{bmatrix} =$$

$$= \begin{bmatrix} \cos v_{i+k} & 0 & \sin v_{i+k} \\ -\sin v_i \sin v_{i+k} & \cos v_i & \sin v_i \cos v_{i+k} \\ -\cos v_i \sin v_{i+k} & -\sin v_i & \cos v_i \cos v_{i+k} \end{bmatrix}$$

It is essential that the substitution of the new argument v in the functional does not alter its important property guaranteeing a tendency to minimum at convex constraints. The set of local minima is equal to the set of global minima for both the functional of the new argument and the initial argument.

The following theorem holds.

Let P(x) be the function on the set X whose set of local minimum points matches the set of the global minimum points. Let $D(y)=x$ be the open mapping of Y onto X. Then the set of local minima $P[D(y)]=\Phi(y)$ is equal to the set of global minima.

In our case the functionals minimized, being the square of the distance to the minima, always have a set of global minima equal to the set of global minima at least. On the other hand let us consider W set on which the functional $R^2(W^*, w_s)$ is chosen to be the set of all kinematically possible spatial positions of the working tool. In this case the expression $w_s=P_o(v)$ mapping V onto W is an open mapping.

Hence according to the theorem the functional $L_o(v)=R^2[W^*, P_o(v)]$ also has identical sets of local and global minima.

Representation of Functionals and Limiting Conditions for the Commands of the Tactical Level

The most characteristic tactical level commands are the following ones:

MOVE THE TOOL TO POINT x (region X*)

MOVE THE OBJECT TO POINT x (region X*)

PREPARE FOR PACKING UP THE OBJECT AT THE POINT

PICK UP THE OBJECT

RELEASE THE OBJECT

BORE FOR A DEPTH OF

SCREWW UP A NUT

The functional

$$R^2(w,w_s) = |w - w_s|^2 = |x_c^k - x_i^k|^2 + \langle (T_c - T), (T_c - T) \rangle \qquad (8)$$

or

$$R^2(w^o, w_s^o) = |w^o - w_s^o|^2 = |x_c^o - x_i^o|^2 + \langle (T_c - T), (T_c - T) \rangle \qquad (9)$$

correspond to the command - MOVE THE TOOL TO A POINT, where:

$w = (x_c^k, l_{*c}^o, m_{*c}^o, n_{*c}^o)$; $w_s = (x_i^k, l_*^o, m_*^o, n_*^o)$;

$w^o = (x_c^o, l_{*c}^o, m_{*c}^o, n_{*c}^o)$; $w_s^o = (x_i^o, l_*^o, m_*^o, n_*^o)$;

x_c^k, x_i^k - are the blocks of the vectors w and w_s which are equal to the given and current positions of the tool in fixed coordinate system;

x_c^o, x_i^o - are the blocks of the vectors w and w_s^o which are equal to the given and current position of the point which is to match the characteristic point of the tool in its coordinate system;

l^{o}_{*c}, m^{o}_{*c}, n^{o}_{*c}, and l^{o}_{*}, m^{o}_{*}, n^{o}_{*}, are the blocks equal to the given and current position of the unit vectors along the axes of the coordinates attached to the tool;

$T = \prod_{j=k}^{j=0} T_{j,j-1}$; T_c is the matrix of the directing cosines for the given position of the tool;

$\langle A,B \rangle$ is the scalar product of matrices A and B.

The command MOVE THE TOOL TO A REGION expresses a less strict demand when one or several components of the goal-setting command vector are not set strictly but are the elements of a certain set. A particular case of this command is one when the region of some component setting is not limited, e.g. the goal-setting command components corresponding to the unit vectors l^{o}_{*c}, m^{o}_{*c}, n^{o}_{*c}. The functional (Exp. 8) without the second term is related to such a command.

One of the most typical commands of the tactical level is the command PREPARE FOR PICKING UP THE OBJECT AT THE POINT... The command is considered to have been executed when the arm acquires a suitable spatial position and when the object to be picked up appears inside the open jaws. In this case the goal-setting command is described by a finite subset of vectors $x^{o}_{c} \in X^{o}_{c} \equiv W^{*}_{o} \subset R^3$ where X^{o}_{c} coresponds to the operating space of the open jaws (Fig. 2). It is described by

$$(-a_1, -a_2, -a_3) \leq (x_1, x_2, x_3) \leq (a_1, a_2, a_3) \qquad (10)$$

where $\pm a_1$, $\pm a_2$, $\pm a_3$ are the boundaries of the admissable region of the components of the vector x^{o}_{c}. It is assumed that the origin of the mobile coordinate system assumes the centre of symmetry of the working region.

The situation vector w_s is related to the point x^{o}_{ob} belonging to the object. It is defined in the coordinate system of the jaws.

The error functional will be

$$R^2(W^{*}_{o}, w_s) = R^2(X^{o}_{c}, x^{o}_{ob}) = |X^{o}_{c} - x^{o}_{ob}|^2 \qquad x^{o}_{c} \in X^{o}_{c} \qquad (11)$$

set X^{o}_{c} being defined by Expression 10.

In the general case when m points on the surface of the object are known, the functional is

$$\sum_{i=1}^{i=m} R^2\left(x^{o}_{c}, (x^{o}_{ob})^{i}\right) = \sum_{i=1}^{i=m} |x^{o}_{c} - (x^{o}_{ob})^{i}|^2 \qquad (12)$$

where $(x^{o}_{ob})^{i}$ is a particular point belonging to the object.

It is clear that minimization of the functional will be reduced to obtaining all the points defined on the object inside the open jaw.

It should be noted that in this case the functional (Exp. 12) may be presented also as the square of the distance $R^2(X, x_s)$ of a certain vector $x_s = (x_{i1})$ $i = 1, 2, \ldots, m$ from subset $X \subset R^{3m}$. $x_{i1} = (x^o_{ob})^i$ is the block of vector x_s corresponding to the i-th point of the object in the coordinates of the jaws. Elements of the subset X are $x = (x_{i1})$, each block $x_{i1} = (x^o_1, x^o_2, x^o_3)^i$ satisfying Expression 10.

The functional (Exp. 12) may be presented as

$$\sum_{i=1}^{i=m} |(x^o_{ob})^i - F((x^o_{ob})^i)|^2 \qquad (13)$$

at the exclusion of x^o_c and considering the compulsory limitations (Exp. 10) on it. Here $F((x^o_{ob})^i) = \| fj1(a_j(x^o_{job})^i)\| (j=1, 2, 3)$ is a vector function whose components are:

$$f_{j1}(a_j(x^o_{job})^i) = \begin{cases} a_j & \text{with} \quad (x^o_{job})^i > a_j \\ -a_j & \text{with} \quad (x^o_{job})^i < -a_j \\ (x^o_{job})^i & \text{with} \quad -a_j < (x^o_{job})^i < a_j \end{cases} \qquad (14)$$

This presentation may also retain for other commands.

If it is assumed that in Expressions 13 and 14 $a_j=0$; $F((x^o_{ob})^i)=0$; m=1 and that $(x^o_{ob})^i$ is the given estimate of some spatial point matching the working tool we obtain the functional (Exp. 9) which is related to the command MOVE THE TOOL TO A POINT... The relation of the tool is not given, and it is assumed that $x^o_c=0$. If the second term of Expression 9 is added to the functional we obtain a full presentation of the command MOVE THE TOOL TO A POINT... (REGION)... Hence

$$\sum_{i=1}^{i=m} |(x^o_c)^i = F((x^o_c)^i)|^2 + \langle (T_c - T), (T_c - T) \rangle \qquad (15)$$

is a generalized form of the functional for the above commands.

When m=1, $a_j=0$, $(x^o_c)^i = x^o_i$ it presents the command MOVE THE TOOL... or MOVE THE OBJECT. If $T_c - T=0$, $(x^o_c)^i = (x^o_{ob})^i$ then Expression 15 corresponds to the command PREPARE FOR PACKING UP THE OBJECT.

The apparent relation of the above functionals to the argument v is to be obtained by means of Expressions 2, 3, 4, 5, 6, 7.

Additional differentiation of the above commands is executed by means of supplementary artificial constrains upon the arguments of the functional which are to be encountered at minimization. For example, the command MOVE THE TOOL TO A POINT can be modified with the help of an additional command to execute the motion of the characteristic point of the tool along a certain path, along a grade in particular.

Typical artificial constraints for this command refer to condition to execute the motion of the tool along a certain path, e.g. a grade. The functional minimization is obtained in this case at

$$(x^k - x_o^k) \times (x_e^k - x_o^k) = 0 \qquad (16)$$

which defines a spatial grade connecting the point x_o^k to x_e^k, corresponding to the initial and final positions of the working tool.

Another example of constraints refer to the command to execute a collinear motion of the working tool, i.e. if the condition $T - T_o=0$ is satisfied, then T_o is the meaning of the matrix T at the initial moment. A simultaneous combination of the two commands is possible. It is also possible to create such a system of artificial constraints upon the functional arguments that an independent command is formed. For example, command BORE FOR A DEPTH OF... and SCREW UP A NUT are modifications of the command MOVE THE TOOL TO A POINT... They are formed when artificial constraints are encountered refering to collinear motion of the borer (wrench) and simultaneous motion of the characteristic point of the tool along the grade coinciding with the axis of symmetry of the tool. The third condition may be one providing the motion of the working tool with the given velocity.

Other type of constraints are due to the environment and certain peculiarities of the construction itself. Such constraints upon the coordinates of the degrees of mobility of the working organ (the arm) are given by the following expression,

$$v_{min} < v < v_{max} \qquad (17)$$

Constraints due to the requirement upon the working organ to avoid the obstacles during execution of the commands may be defined in two ways.

The first one is based on the assumption that the type and position of the obstacle arm known, so that it can be approximated by the intersection of two "m" planes forming a convex region with the working tool inside it. In this case minimization of the functional can be curried out taking into consideration the system of inequalities 18 which specifies the requirement that the region of the working tool and the region of the above planes should not intersect (region of the working tool can be approximated well enough to the k-1 unity of convex bodies)

$$\left((x^k)^{i,j} - (x^k_{surf})^{\mu}\right)\cdot (q^k_{surf})^{\mu} \le 0 \qquad (18)$$

$$j = 1, 2, \dots, n$$
$$i = 0, 1, \dots, k-1$$
$$\mu = 1, 2, \dots, m$$

where:

$(q^k_{surf})^{\mu}$ is a normal to the μ-th plane at the point $(x^k_{surf})^{\mu}$,

$(x^k)^{i,j}$ is the vertex of the parallelepiped related to the j-th joint.

The second way of defining the constraints does not require an a priori knowledge of the parameters of the obstacles. In this case the constraints are specified by the system of the inequalities of the type:

$$M_i(v) \le M_{i\ max} \qquad i = 1, 2, \dots, n \qquad (19)$$

where $M_i(v)$ corresponds to the moment of resistance developed in the relevant working organ while in contact with an obstacle.

As the relation of $M_i(v)$ on V is unknown regularly it is necessary to determine its linear approximation in a small surrounding Δv of its current value v. It is performed by means of trial steps δv applied to each coordinate of the degrees of mobility and by computing the moments and their increments in the relevent drive.

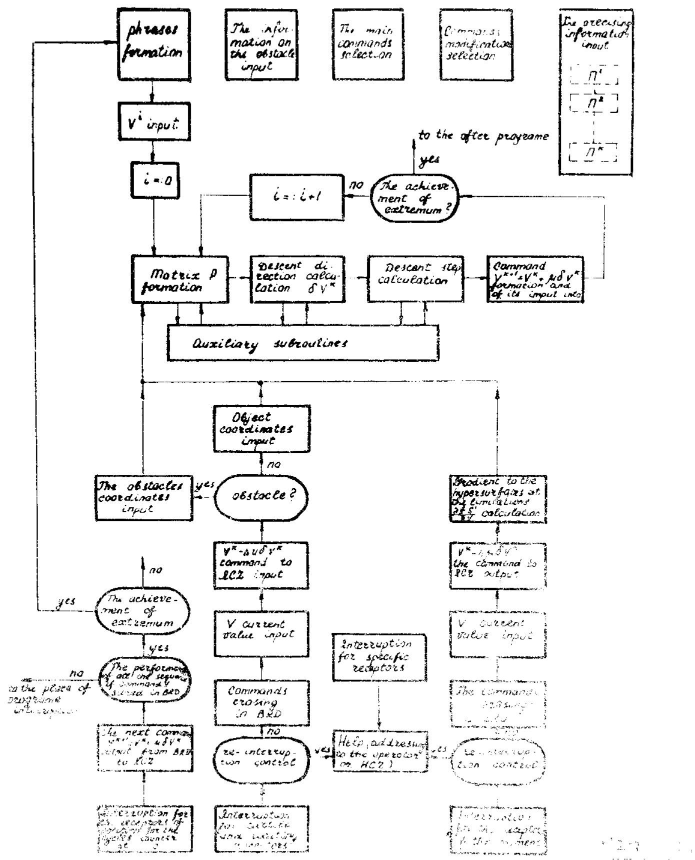
The apparent relation of the natural and artificial constraints upon v can be obtained through Expressions 2, 3, 4, 5, 6, 7 as in the case of the functionals.

Minimization Algorithm of Functionals on the Tactical Level

When chosing optimization method it is important to take into consideration that becides the minimum value of the functional is to be determined, the shortest way to it should be found. The algorithms based on the gradient methods with the finite step (Zontendeik's method of admissible directions /7/ for example), seem to be staisfactory. This method ensures the

the path of motion to the goal "along" the gradient or close to it, in case when additional constraints upon the argument step are provided. The character of functionals related to the command of the tactical level provides the shortest way to the goal in the space of the arguments. The chosen minimization algorithm together with the algorithm for forming a matrix of natural and artificial constraints upon the argument depend very little on the type of commands on this level. Thus these algorithms form the basic computing program of this level which provides the realization of a variety of commands.

Figure 3 illustrates a generalized block diagram of the tactical control level program. The program includes special input blocks for both the commanding information and the initial minimum information on the environment needed for the basic computing



program. This information is introduced by the operator who realizes the superior control level.

The basic computing program forms a cycle. It produces a command for the inferior control level as the result of the cycle completion. In general either the extremum is achieved or cycling is interopted by the signal from the receptor in order to provide the specification of the environment.

The methods discussed in the paper were tested in 1968 when an autonomous device was built consisting of an electrohydraulic arm and a YMI-HX computer. In 1970/71 another robot was tested where the described methods of control organization were applied.

The hands of a standard MEM-10 manipulator with carrying-capacity of 10 kg were used as its working parts. The hands were modified so that they could be controlled by a computer. They were also capable of supplying information via tactile transductors and transducers of position and effort. "Dnepr-I" computer was used to control the robot. Communication between a man and a robot was performed by means of a "tele-eye" and a programming panel. The tele-eye is a special TV unit with the foreseen possibility of setting the place where commands are executed on touching with the "light-pen" the relevant point of the transmitting tube shield on which the TV stills of robot environment are shown. The programming panel is a keyboard for inputing the programs in a problem-oriented language. The results of testing conformed the effectiveness of the methods suggested.

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