TELEROBOTIC SYSTEMS WITH MANIPULATOR PARAMETER CONTROL

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Abstract

An approach to telerobotic system organization with manipulator variable parameters is presented. It is intended for solution of manipulation problems when fast transportation operations are combined with high precision positioning operations. The use of accuracy and fast-operation criteria for the design of remotely controlled manipulators is based on the fact that altering the values of manipulator parameters influences the telerobotic system quality. An experimental investigation was performed to determine this influence. The investigation results showed that the most influential parameter is manipulator gain. Therefore, it was chosen as a mean for system quality control. It was proposed that the human operator should personally adjust the robot parameters in compliance with the situation requirements. Therefore, an additional channel of parameter control was introduced into the system. The approach results in the organization of highly effective on-line systems with sufficiently simple control algorithms.

Keywords: manipulator, telerobot, remote control, variable parameter.

1 INTRODUCTION

The optimal co-ordination of a human operator (HO) and a robot under manual control remains a problem in many applications. However, the concept of optimal co-ordination in man-machine system is, itself, not exactly defined and is approached in various ways. At the same time, it is obvious that this co-ordination should incorporate machine development that ensures the most convenient HO work and results in an improvement of system quality. On the other hand, there are quantitative criteria of remote control quality [5,13] that may provide indices of the co- ordination range of HO and controlled manipulator characteristics. In this way, the outlined reasoning leads to a conclusion that optimal co-ordination of HO and manipulator must always increase the work quality.

An increase in the quality of telerobotic systems is important because these systems are used in very responsible and complicate operations and must work accurately and rapidly. Mounting and assembly works in nuclear power stations, in space, and in underwater environments belong to this class of operation. High requirements are placed upon industrial robots controlled by an HO. As a rule, there are some difficulties under operation in the realization of fast transporting motions or highly precise positioning. The most common way to satisfy these requirements is to use semi-automatic control systems with variable structure [8,9,10]. Such systems, for example of a hybrid position-rate type, permit us to achieve maximum effect with respect to the accuracy and speed.

However, the problem is that such systems are very complicated and this always entails high cost and low reliability. This is the reason for the very limited practical application of these systems, though they have been well elucidated in the scientific and patent literature. Thus, the problem of developing on-line methods for different kinds of telerobotic control is very real and has given rise to numerous investigations [11].

This paper presents some fundamentals that lead to telerobotic organization with variable parameters and enable simple and effective remote control systems to be developed.

2 QUALITY CRITERIA SENSITIVITY TO MANIPULATOR PARAMETER ALTERATION

Of the telerobotic system quality indices [1], the most important are the criteria for accuracy and speed of a manipulation operation performance, all other factors being equal. The application of these criteria during system quality analysis [5,13] has indicated their use in evaluating the abilities of various operators controlling the same manipulator, as well as the quality of different manipulators controlled by the same operator.

Use of these criteria under remote control design for perspective techniques is based on the fact that alteration of the parameter values of a controlled manipulator influences the system performance quality. The determination of this influence was a purpose of the experimental investigation carried out with the help of semi-natural simulation methods [5]. The remote control process of the position-type two-coordinate manipulator has been studied. During the investigation on the layout of Fig. 1, the HO controlled the plane Cartesian manipulator linear model (M), realized on an analog computer (AC), using a two-coordinate setting device (SD).

For each control channel, a dynamic manipulator model was adopted for the oscillating unit and was realized in the form of the identical transfer function

$$W_x(p) = W_y(p) = \frac{k}{T^2p^2 + 2T\xi p + 1} ,$$

where T is period of model free vibrations, ξ is the damping coefficient, k is the model gain.

The output point of the executive organ model was displayed in the form of a mark on the oscilloscope (O) screen. The control task for the HO was a fast and precise tracing of a prescribed closed curve (specifically, a circle) plotted on the oscilloscope screen, using visual feedback. During task execution, the measuring apparatus (MA) was switched on with the help of the automatic device (AD) and registered the total time To of the control cycle and the system integral quality index in the form

$$J = \int_0^{T_0} [\rho(t) - \rho_r(t)]^2 dt , \qquad (1)$$

where ρ is the module of radius vector of the trajectory realized by the operator and ρ_r is the module of reference trajectory radius vector. Index (1) is approximately equal (with an accuracy of co- multiplier [13]) to complex criterion

$$J \approx T_0 \cdot \Phi = T_0 \int_{\phi_0}^{\phi_{T_0}} [\rho(\phi) - \rho_r(\phi)]^2 d\phi \,, \tag{2}$$

where Φ is the integral error of curve tracing and ϕ is the polar angle.

Using registered results To and J, the calculation of the accuracy index Φ was produced. The end goal of the investigation at this stage was to obtain the dependencies

$$J = f_1(k),\ J = f_2(T),\ J = f_3(\xi),$$
$$T_0 = f_4(k),\ T_0 = f_5(T),\ T_0 = f_6(\xi),$$
$$\Phi = f_7(k),\ \Phi = f_8(T),\ \Phi = f_9(\xi).$$

Based on these dependencies, the relative sensitivity coefficients were calculated for each quality criterion J, Φ, and To, with respect to each alteration of parameters k, T, and ξ, during the experiment. The corresponding sensitivity coefficient values based on statistically treated experimental data are adduced in the Table.

Quality Criterion	T_0	Φ	J
Varied Parameter			
k	2.49	2.18	8.75
ξ	0.9	0.7	5.99
T	2.4	0.07	0.9

Table 1: Values of the relative sensitivity coefficients

It is evident from the Table data that the manipulator model gain k had the greatest influence of all of the criteria. At the same time, the parameters ξ and T variously influenced the criteria J, Φ, and To. The vibration period T had a greater influence on the task fulfillment speed and the damping coefficient ξ had a greater influence on the system accuracy and the complex criterion J.

Hence, if there is a need to accomplish work in an optimal regime, the manipulator gain is the first parameter that should be tuned. One of the ways of carrying out such tuning is by setting up the optimal gain values for all the controlled manipulator channels. This may be done, for instance, by means of control system amplifiers adjusted beforehand.

For such adjustment of the gain value, one has to be sure that the optimal parameter value is approximately constant in the HO work and there is no prevailing tendency for it to change over time. To ascertain this, another experimental research has been carried out.

3 THE INFLUENCE OF MANIPULATOR GAIN OVER TELEROBOTIC SYSTEM WORK QUALITY

The work quality study of a telerobotic system with manipulator gain tuning was based on the methods described in the previous section (Fig. 1). An inertialess model with rate control using equation

$$\dot{y}_2 = \eta \cdot y_1 \quad , \quad \dot{x}_2 = \eta \cdot x_1 \ ,$$

where $\eta[\sec^{-1}]$ is the gain of the rate manipulator, x_1 and y_1 are input signals from a setting device, x_2 and y_2 are output signals of the manipulator model, was studied in this case. The efficiency criterion (2) was calculated. Gain η tuning was executed based on a segment where the optimal value of the parameter

$$\eta_0 = \arg J(\eta)|_{J=J_{min}}$$

was determined.

Under investigation were six values of parameter η: 0.135; 0.2; 0.675; 1.35; 2.025; and 3.375. The experimental procedure is described below.

In order to determinate the optimal gain value $\eta = \eta_o$ and its change in time, a permanent scanning was carried out on enumerating values of the parameter η within the selected segment. The scanning was performed in straight and reverse directions alternately. This was done in order to avoid large jumps in the gain that would have caused the operator's work quality to deteriorate due to his loss of control skill in the process. For each gain value, a reference trajectory tracing was executed. For scanning each cycle, the optimal value ho was determined. Thereby, a set of characteristic results was obtained, despite all the random errors accompanying the HO work.

The alteration of the optimal gain η_o vs. the number N of the tracing cycle (scanning) is shown in Fig. 2 (the continuous line). It can be seen from this diagram that the optimal value of $\eta_o = 3.375\,\text{sec}^{-1}$ remained about constant with some exceptions during almost the whole experiment. It is necessary to take into account the fact that the described investigation was accomplished over a lengthy period (up to six hours). Thus, it is possible to conclude that a certain optimal value of the manipulator gain for every operator remains fairly constant during the whole working day.

In the experimental process, the criterion (2) with simplified accuracy component

$$J^* = T_0 \int_0^{T_0} [\rho(t) - \rho_r(t)]^2 dt \,, \tag{3}$$

was also calculated. Another sequence of the optimal values ho corresponds to this criterion (the dotted line in Fig.2). It is important to note that the different criteria (2) and (3) have different optimal values of η_o.

The effectivity question of the chosen optimal manipulator parameter is also important. It is necessary to clarify whether this parameter will really effect a system quality increase. To determine this, the values of the complex criterion J (in relative units), corresponding to the optimal parameter value $\eta_o = 3.375\,\text{sec}^{-1}$, were selected from the results of the tracing of each cycle. Their sequence vs. the tracing cycle number N is adduced in Fig. 3 (the continuous line).

The values of criterion J for the nearest approach to optimal gain η_o value $\eta_1 = 2.025\,\text{sec}^{-1}$ were also selected and they are also adduced in Fig. 3 (the dotted line). It is clear that the line $J_{\eta_o}(N)$ has settled down almost everywhere below line $J_{\eta_o}(N)$. On the considered interval the average value of criterion J for η_o is $\overline{J}_{\eta_o} = 675$ and for η_1 is $\overline{J}_{\eta_1} = 963$. This indicates that for optimal gain value, the system quality is 30% higher than for the nearest gain value η_1. The presented results testify that the described way of manipulator parameter tuning, significantly improves telerobotic system performance.

4 OPERATIVE ADJUSTING OF MANIPULATOR PARAMETERS

4.1 The basis of the method

In spite of the remarkable increase in manual control quality, the described technical solution freezes the manipulator parameters and does not permit the rapid alteration of its indices when operation requirements change. It is therefore a worthwhile method in cases where the manipulation system performs technological operations that do not require maximum accuracy or fast-operation. If such the requirements appear, another technical solution is needed to change flexibly the system characteristics.

Such a solution essentially requires the HO himself to adjust the manipulator parameters during the control process according to changing technological requirements. The additional channel of parameter control is then introduced into the system.This channel acts simultaneously with the main coordinate channel, that is with the control channel of generalized manipulator coordinates. Such an approach results in the organization of semi-automatic control systems with variable parameters unlike the better- known semi-automatic control systems with variable structure [9,10]. So, a new class of coordinate-parameter control (CPC) systems for robots is obtained.

An extended block diagram of such a system is shown in Fig. 4. The notations include: M-a controlled manipulator, g-an input signal, x-an output signal, f-a disturbing influence, u-a controlling coordinate signal, and y-a supplementary controlling parameter signal. The HO model shown here consists of two blocks: the traditional controller of coordinate control CCC and, in addition, the new controller (with the new operator's function) of parameter adjustment CPA.

Then, a new unit of CPC appears in the robot control system. The general block diagram for a remote manipulation system of the tactical level can be seen in Fig. 5. To control three main degrees of freedom of the manipulator, it contains a hand controller HC, and a control block CB, where CPC algorithms are realized in the subblock CBP. The subblock CBT performs the traditional functions of generalized coordinate transformation. It produces signals $\phi_1(t)$, $\phi_2(t)$ and $\phi_3(t)$ for control of the manipulator drives D1, D2, D3.

The CPC algorithms for the subblock CBP can be obtained by using the mnemonicability principle [6]. This means that the shift vector $\Delta\overline{X}$ of the control handle must be collinear to the shift vector $\Delta\overline{Y}$ of the manipulator hand gripper (Fig. 6). Let me explain here that values $\overline{X}_0$ and $\overline{Y}_0$ characterize the positions of setting and executing organs respectively, before shift operation fulfillment; vectors $\overline{X}$ and $\overline{Y}$ characterize the positions of the same mechanisms after fulfillment of an elementary motion act by the HO. As this take place, the mnemonicability local coefficient for position system is defined [6] as correlation

$$k_m = \frac{(\Delta\overline{X})^T(\Delta\overline{Y})}{|\Delta\overline{X}||\Delta\overline{Y}|} ,$$

which is equal to the cosine of the angle between $\Delta\overline{X}$ and $\Delta\overline{Y}$. It is obvious, that the value k_m has maximum equal to one, when this angle equals zero. So, the vectors $\overline{X}$ and $\overline{Y}$ are collinear and this fact may be written down as the formula

$$\Delta\overline{Y}(t) = k\Delta\overline{X}(t) , \tag{4}$$

where k is the positive scalar value.

If the the scalar k is the constant value, the relation (4) characterizes the ordinary position control with the constant scale coefficient $k = const.$

This scalar may also be a variable value $k(t) = var$. This version corresponds to the CPC case.

The hand controller of this system usually differs from the others. It has the possibility of setting up both the control coordinate signals and the parameter signal. Such a hand controller is presented in Fig. 7.

We should note that the means for the coordinate control are only partly shown. In the first place, the figure illustrates that this device incorporates a special reference input element for setting the parameter signal. It works when an operator squeezes the elastic handle H and the stop S presses on the elastic plate P. The plate deforms and transducer T (here the strain gage) gives the control parameter signal, that proportionally connects the handle squeezing force F and the manipulator gain k:

$$F(t) = a \cdot k(t) \ , \ a = const.$$

During the control process, an operator continuously introduces into the system the maximum gain value when executing transportation movements, and the minimum gain value when executing operations with a high accuracy.

The above procedure permits very simple and effective telerobots with flexible control to be set up. The simulation indicates the high quality level of these systems. The elaboration of remote control systems for the real industrial robot teaching was also performed by the author when he worked in the Kazakh State University (Alma- Ata City, the former USSR).

4.2 CPC mechanical realization

In some cases, another approach to CPC realization is required due to impossibility of implementing the described principle of gain adjustment in a manipulator control system. For example, in master-slave systems, it leads to deterioration of the mnemonicability [6] and, as a consequence, of system accuracy [2]. Another method of CPC realization may then be proposed based on the fact that the resultant system gain is the product of the gain of the system control part (k_c) and the gain of the mechanical part (k_m)

$$k = k_c \cdot k_m.$$

Thus, if control of the value k_c is impossible, it may still be possible to control the gain k_m. Practically, the latter is the manipulator scale coefficient. In master- slave systems, this coefficient may, in turn, be controlled by one of two methods.

The first utilizes scale alteration of the slave arm mechanism. In order to implement it, the lengths of its links must be made variable, for example, in pantographic or telescopic form. The characteristics of this case are described in [2].

Fig. 8 shows the executing manipulator's hand in the base plain which uses joint-lever mechanisms pantographs as the hand's links (shoulder and forearm). The mechanism of the hand's rotation in the shoulder joint is not presented here. The pantographs of shoulder and forearm consist of the details, 1 - 4 and, 5 - 8, respectively. The manipulator also contains the gripper, 9 and the driving motors,10. Motion translation to the pantographs is brought about from the motor,11 via the gear transmission with the drive gear, 13 and gears, 16 and 17. Realization of the required modes of the manipulator's operations is obtained by means of the use of commutation elements - friction electromagnetic cluthes.

Under synchronic motion of drives for the link lengths alteration, a manipulation system scale coefficient is changed and, accordingly, its quality indices. It is obvious that in this case the construction of the executive manipulator organ gets rather complicated, but achievable effect is not only limited by the advantages of the CPC method. Moreover, the mechanical arm can perform a broad range of new technological operations at the sacrifice of kinematic redundancy in the mechanical arm structure. As this take place, its accessible area volume is increased, its non-utilizable area volume is decreased, and manipulator maneuverability and service are increased. Such manipulators also allow us to avoid collisions and to organize effective motions of a robot hand in environments with obstacles [7]. The construction of mechanical arms that permit these problems to be solved, are proposed [2]. A provision is made for realization of described functions without increase in the number of drive motors. All that is required is at the placement of some commutative elements, for example, the electromagnetic muffs, in the drive .

The problem in hand can also be solved by making the links of the master arm of variable lengths. Such a master- arm setup is shown in Fig. 9.

This arm contains the base, 1, the joint-connected telescopic links, 2 - 4 and the handle, 5. The position sensors, 6 are situated in the joints. The slots, 7, are cut in the links, 2 - 4. The fingers, 8, are placed there and firmly attached to the inner elements, 9, of the telescopic links. The ropes, 10, connect the fingers to the motor, 11, specifically used to alter the length of the master-arm links.

Controlling this arm, an operator moves its links 2 - 4 by using the handle. Signals to the slave arm control are taken from the sensors. When it is necessary to use the slave arm at high velocity, an operator increases the manipulator scaled coefficient, by pressing button, 12. A movement from motor, 11, is passed to the inner elements of the links. The elements are pushed into the links which are proportionately shortened. If it is necessary to carry out a high-accuracy operation, the operator presses button, 13 for reverse motion of the motor. The springs, 14 pull out elements, 9. The link lengths increase and the scale coefficient decreases. A change in the manipulation system quality indices also occurs but this method is indeed simpler and cheaper. Although the kinematic advantages of the first solution are then lost the simplicity of the second system may often be more important.

5 CONCLUSION

Alteration of parameter control provides new possibilities for the development of different kinds of robot. In principle, the approach is related to the gain alteration well-known in robotics, particularly in master- slave systems [12]. But usually, the gain changing is realized by switching which poses challenges to a human operator. Firstly, the switching may cause complicated dynamic processes in the system. Furthermore, it requires the operator to adapt to a new gain value, leading to loss of operator skill and needing operator re-education. It is clear that these factors reduce the quality of the operator- manipulator system performance.

In CPC systems, these problems practically disappear because the transition process from one value of the gain to another is continuous. In addition, this kind of system has very simple control algorithms as compared to the hybrid systems of position-rate control [9,10] that have the same purpose. As a result, CPC systems enjoy lower cost and higher reliability.

The CPC method may be used not only for the tactical level of remote systems but also for manipulator servo systems and optimal automatic systems of the executive level [14]. It represents a rather common approach for machine control problem solving.

Summing up, we should note that the distribution of functions between control channels in the CPC system is follows: 1) as is normal, the coordinate control circuit ensures a realization of the main control goal. For a position type manipulation robot this means that the desired positioning point is achieved. 2) In the parameter control circuit, it is used to improve (optimize) the control process quality indices. It is obvious that when the requirements of system quality increase because extra quality criteria are added, the number of an object regulating parameters must also be increased. It seems reasonable to say that determining some tie between these two indices would be regarded as successful progress in the field.

The use of the CPC method in telerobotic systems is now more advanced with respect to other applications of the method. It indicates that there are good prospects for the development of advanced teleoperation systems [3,4] and other present-day machines, controlled by HO.

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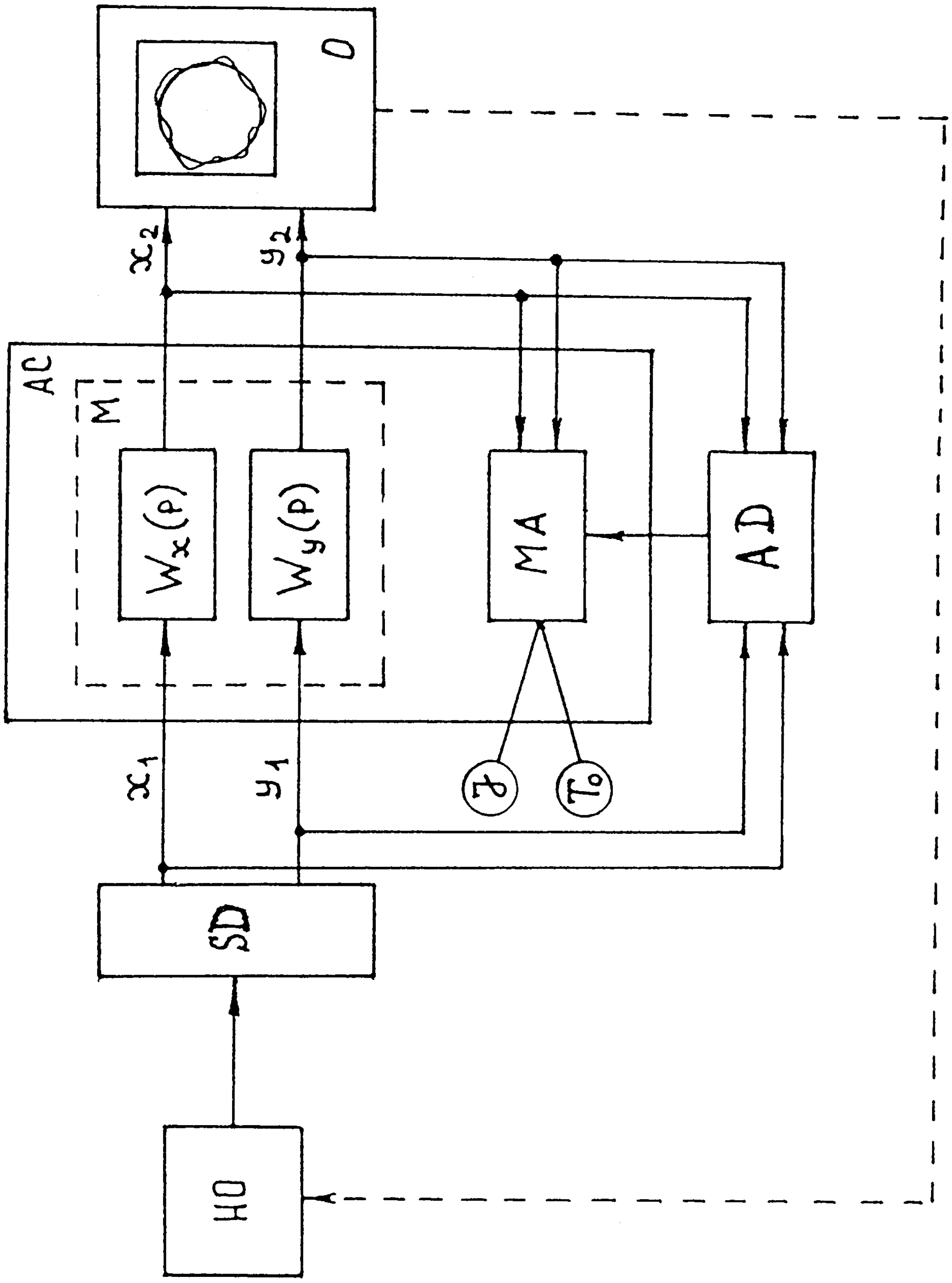
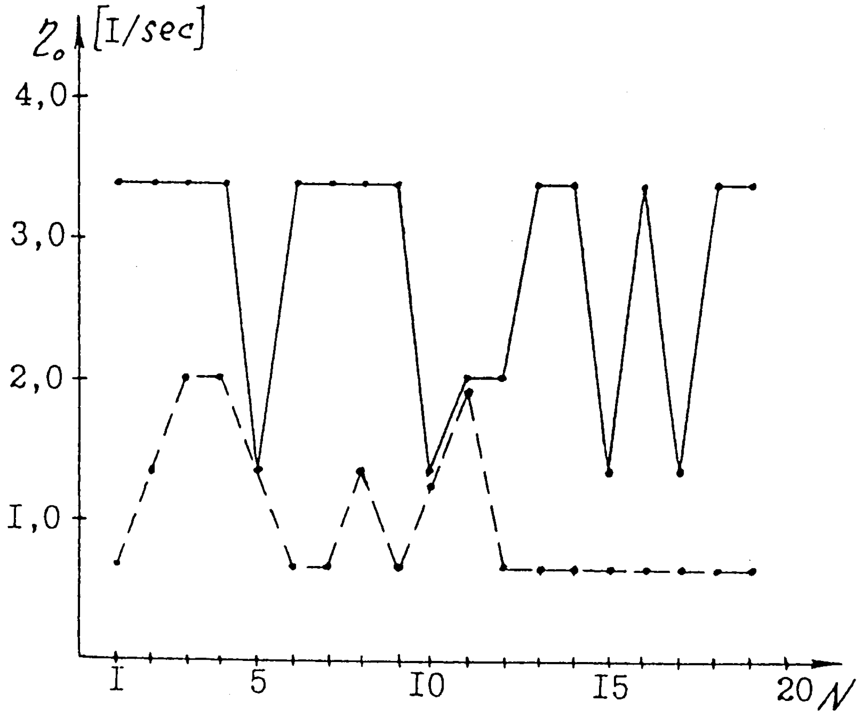


Fig.1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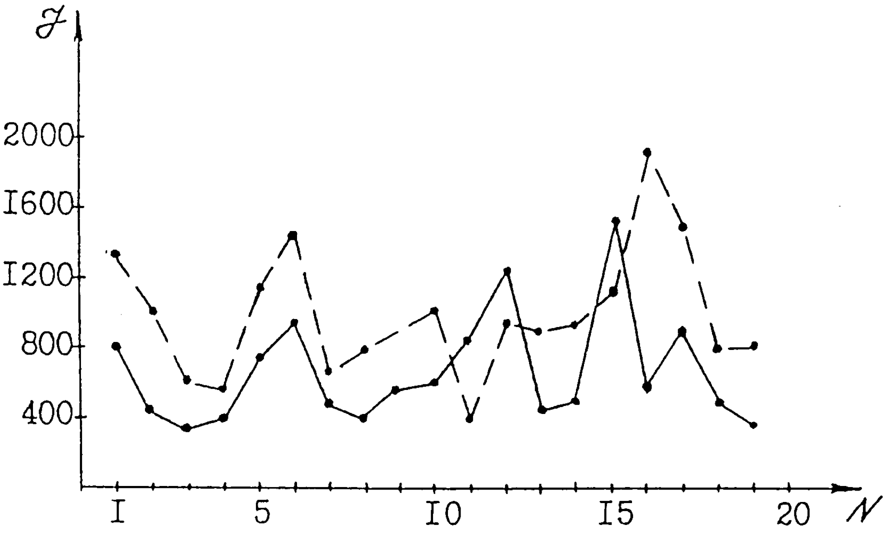
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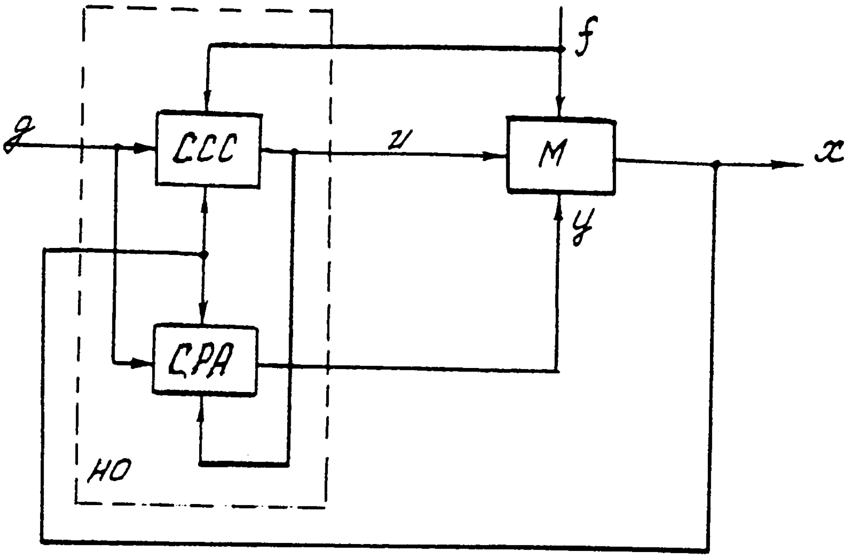
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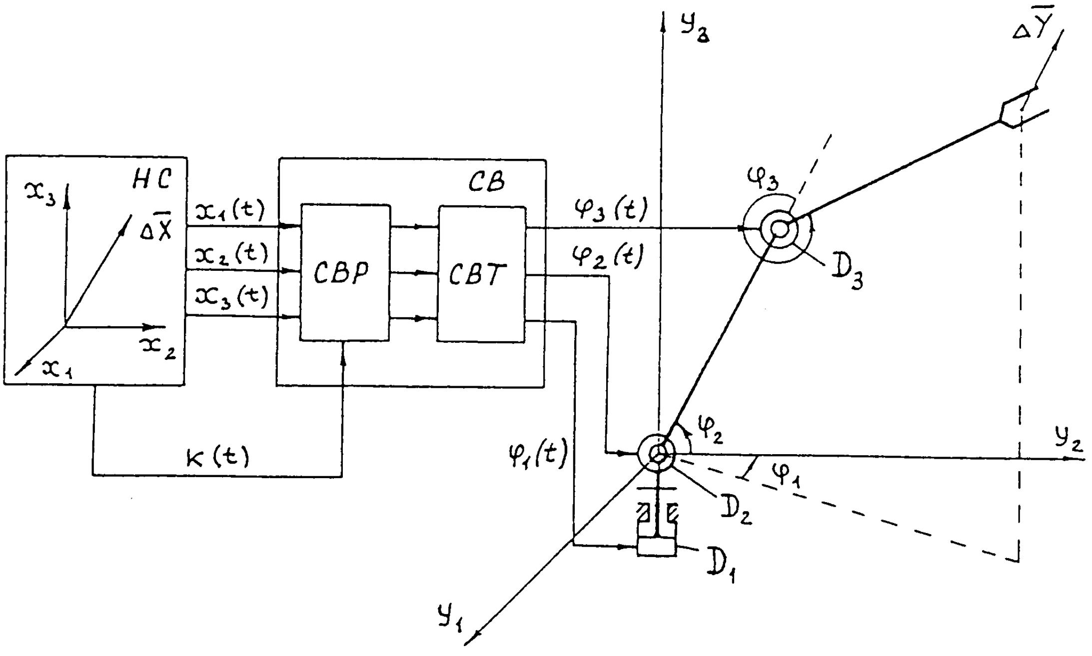
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Fig.5

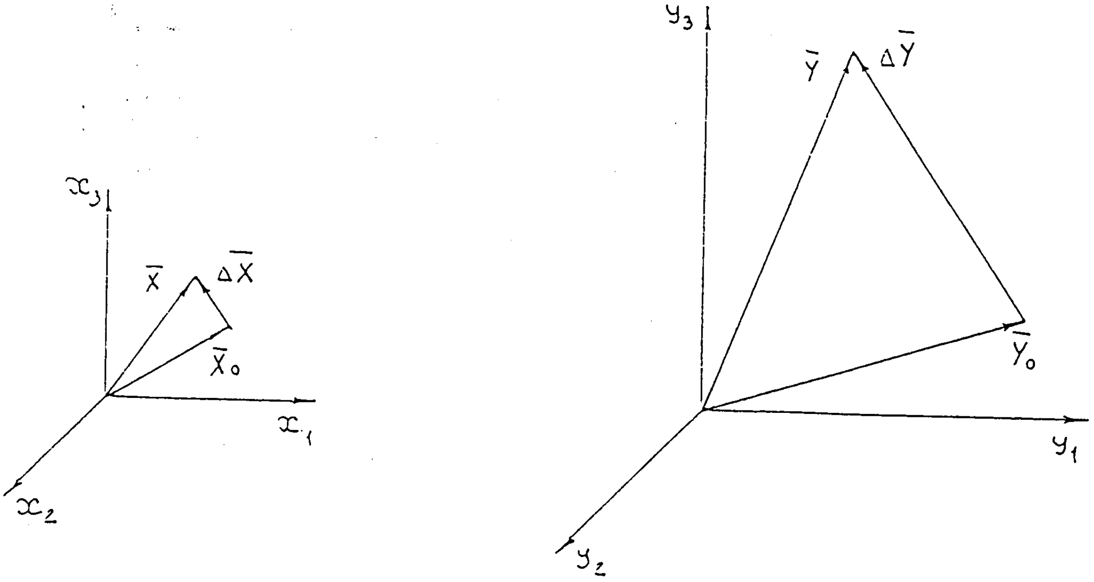


Fig.6

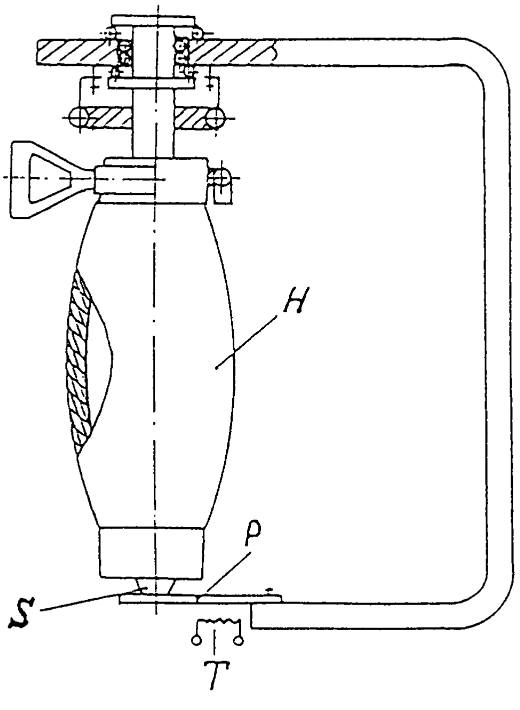
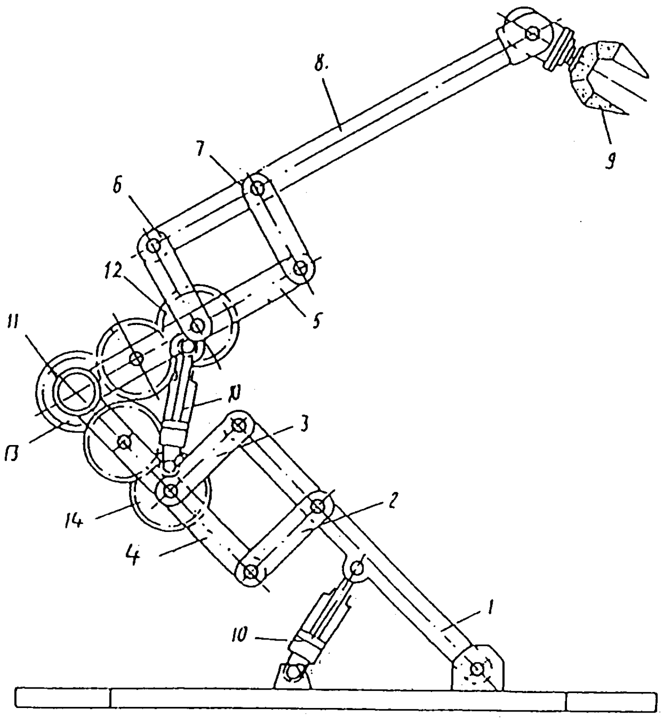


Fig.7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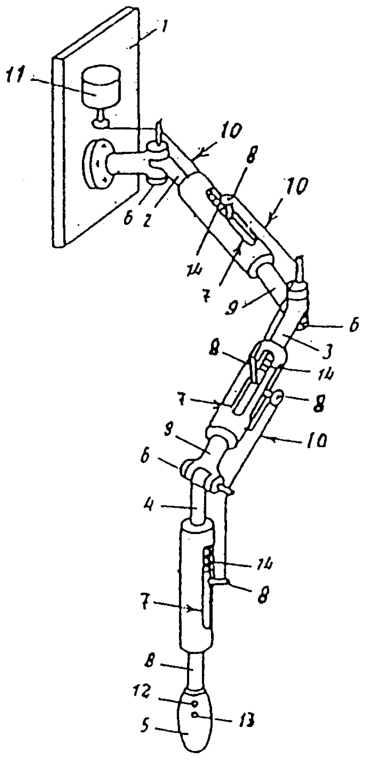
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Fig.9