Online Telecontrol Techniques Based on Object Parameter Adjusting

Abstract

An approach to telerobotic system organization with manipulator variable parameters is developed. It is intended for solution of manipulation problems when fast transportation operations are combined with high-precision positioning operations. Based on previous research, manipulator gain was chosen as a means for system quality control. It was proposed that the human operator should personally adjust the robot parameters in compliance with situation requirements. Besides such direct parameter adjustment, another implementation of this concept based on indirect adjustment (such as by analog circuit) was also developed. An additional channel of parameter control was introduced into the system in these cases. A new hand-controller design and a method for synthesis of such system algorithms were also developed. The ground has thus been laid for the kinematic coordinate-parameter control for the main regimes of telerobot work. The described approach results in the organization of effective online systems with sufficiently simple control algorithms. By means of testing, the efficiency of these systems is shown.

1 Introduction

The practical needs of teleoperation demand a further development of remote robotic systems. An increase in the quality of telerobotic systems is important because these systems must work accurately and rapidly (Bejczy, 1994). For example, 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 a human operator (HO).

Such demands are extremely various (Sheridan, 1992; Vertut and Coiffet, 1985), but it is possible to distinguish a number of cardinal ones:

- high positioning accuracy associated with control system resolution;
- very fast operation associated with achievement of a high rate of change in the output signal;
- system universality, e.g., flexibility in adapting to different work regimes;
- system simplicity, leading to reliability and low cost.

These demands are contradictory and, as a rule, they must be met by different types of control systems. Thus, for example, high accuracy and simplicity are provided by an on-off control system with speed adjustment. Such a system, however, is characterized by slow operation. A master-slave control system is
quite simple to install and may be fast enough, but it almost always lacks sufficient precision. Lastly, there is semiautomatic control. While this control ensures high accuracy and speed, it uses combined systems with variable structures (Malone, 1973; Medvedev, Leskov, and Yushchenko, 1978; Melton, Rose, and Hedin, 1971) that make it highly complicated, and therefore its consequences are less desirable. Thus, there has been very limited practical application of semiautomatic systems, for instance, in industrial robotics, although these systems have been well elucidated in the scientific and patent literature. The problem of developing an online method for different kinds of telerobotic control is therefore very real and has given rise to numerous studies (Rahimi and Karwowski, 1992).

Since conventional control approaches are not always successful, we must look for new methods to attack telecontrol problems. By way of an alternative approach, let us consider the method of coordinate-parameter control (CPC), which was first proposed to control automatic nonstationary objects (Petrov, Zemlyakov, and Rutkovsky, 1980). The use of CPC in robotics relates to a specific class of controlled objects and new ways of solving control problems (Slutski, 1994; Slutski and Coiffet, 1996).

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

2 Operative Adjusting of Manipulator Parameters

2.1 The Basis of the Method

Of the telerobotic system quality indices (Sheridan, 1992; Vertut and Coiffet, 1985), the most important are the criteria for accuracy and speed of a manipulation operation, all other factors being equal. The application of these criteria during system quality analysis (Kobrinskii et al., 1974) has indicated their usefulness 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 advanced techniques is based on the fact that alteration of the parameter values of a controlled manipulator influences system performance quality. Results of the experimental investigation show that if there is a need to accomplish work in an optimal regime, the manipulator gain is the first parameter that should be tuned (Slutski, 1994). By physically changing the gain, a changing of the system scaling results.

To make the system characteristics flexible, a solution was proposed that essentially requires the HO himself to adjust the manipulator parameters during the control process according to changing technological requirements (Slutski, 1994; Slutski and Coiffet, 1996). An additional channel of parameter control is therefore introduced into the system. This channel acts in parallel with the main coordinate channel, that is, with the control channel of the generalized manipulator coordinates. Such an approach results in an organization of semiautomatic control systems with variable parameters that is unlike the organization of better-known semiautomatic control systems with variable structure (Medvedev, Leskov, and Yushchenko, 1978; Melton, Rose, and Hedin, 1971). Thus, a new class of adaptive CPC systems for robots is obtained.

The general scheme of the remote adaptive system is largely similar to a scheme for automatic CPC systems (Petrov, Zemlyakov, and Rutkovsky, 1980). But further detailed implementation of the method differs completely from the latter.

To use this approach, a new CPC unit must be included in the robot control system. The general block diagram for a telerobotic system can be seen in Figure 1. It contains a hand controller and a control block CB, where adaptive algorithms are implemented in the subblock CBP. The sub-block CBT performs the traditional functions of generalized coordinate transformation, producing signals $u_1(t) \ldots u_n(t)$ to control the manipulator drives.

2.2 Position Control Algorithm

The adaptive algorithms for the sub-block CBP (Figure 1) can be obtained by using the mnemonicabil-
ity notion that was introduced by A. Kobrinskii and his colleagues for master-slave systems (Kobrinskii, Stat-
senko, and Tyves, 1975). If we designate the vector of
the master endpoint movement by \( \Delta X \) and the vector of
slave gripper point movement by \( \Delta Y \), then the cosine of
the angle between \( \Delta X \) and \( \Delta Y \), which is expressed by the
formula

\[
k_M = \frac{(\Delta X)^T (\Delta Y)}{|\Delta X||\Delta Y|}
\]

for the certain arm configuration, was named as a local
coefficient of mnemonicability.

Developing this approach for semiautomatic systems,
this means that, in the position control case, the shift
vector \( \Delta X \) of control handle CH must be collinear to the
shift vector \( \Delta Y \) of manipulator hand gripper G (Figure
2). The values \( X_0 \) and \( Y_0 \) characterize the positions of
input and executing organs, respectively, before shift
operation fulfillment; vectors \( X \) and \( Y \) characterize the
positions of the same mechanisms after execution of an
elementary motion by the HO.

As this takes place, the mnemonicability condition for
the position system (Slutski, 1994; Slutski and Coiffet,
1996) may be written down as the correlation

\[
\Delta Y(t) = k\Delta X(t)
\]  

(1)

where \( k \) is the positive scalar value.

If scalar \( k \) is a constant value, relation (1) characterizes
the ordinary position control with the constant scale
coefficient \( k = \text{const} \).

The scalar may also have a variable value \( k(t) = \text{var} \).
This version corresponds to the adaptive control case.

For the latter case let us move on to the differentials in

\[
Y(t) = \int_0^t k(t)X(t)\,dt, \quad Y(0) = 0
\]  

(2)

When \( k(t) = k = \text{const} \), we obtain from (2) the corre-
tion for conventional coordinate control:

\[
Y(t) = kX(t)
\]  

(3)

The control device layout for one controlled channel
on Figure 3a corresponds to the algorithm described in
Eq. (2). In this layout, the following designations are
labeled (in addition to those used in Figure 1): I is an
integrator, D is a differentiator, M is a multiplier. In this
case, the integrator I acts also as the memory. Lastly, this
device structure may be further simplified if the velocity
transducers are used as the sensors (Figure 3b). The
need for differentiator D will thus be avoided and, as
result, the obtained device will be even simpler.

The hand controller of this system usually differs from
that used in other systems. It has the possibility of set-
ing up both the control coordinate signals and the pa-
rameter signal. An example of such a hand controller is
presented in Figure 4. Coordinate control signals are
produced here in analogy to known systems of semiauto-
matic control. The HO moves handle H and determines
its desired transferences in space, which are fixed by sen-
sors S-X, S-Y, and S-Z (here, the strain gauges). These
set a manipulator arm motion in space. In this example,
the input device also has sensors S-r and S-h (the poten-
tiometer gauges), which set motions of the rotation and
Figure 3. Layout of the adaptive position control device for one channel for (a) a hand controller with position sensors (b) a hand controller with velocity sensors.

clamp of the manipulator gripper. The handle also incorporates a special reference input element for setting a parameter signal. It works when an operator squeezes the elastic handle H and stop S presses on elastic plate P. The plate deforms and sensor S-k (the strain gauge) gives the control parameter signal that proportionally connects the handle squeezing force \( F(t) \) and the manipulator gain \( k(t) \):

\[
R(t) = a \cdot k(t), \quad a = \text{const.}
\]

A similar suggestion on how to build a hand controller was made in (Fiorini et al., 1987) but for other purposes.

During the control process, by changing the squeezing force \( F \) of handle H (Figure 4), the HO continuously introduces into the system the maximum gain value when executing transportation movements and the minimum gain value when executing operations requiring high accuracy. The above procedure permits very simple and effective telerobots with flexible control to be set up.

2.3 Rate and Acceleration Control

Let us remember that the mnemonicability notion was introduced (Kobrinskii, Statsenko, and Tyves, 1975) only for master-slave systems. Based on the main definition, we wrote correlation (1) to apply to semiautomatic position systems, taking into account the coincidence of the vector directions of the input handle and manipulator gripper shifts.

Passing on to the higher-order systems, we must also obtain a correlation that characterizes such a system’s mnemonicability. At the beginning, however, it is necessary to stress that remote adaptive position control use ensures high accuracy and speed characteristics (see below), and, in practice, it is not normally worthwhile to
built rate and combined position-rate systems. However, acceleration (force) control is another matter. Such systems may be very widely used in practice—for example, in combination with position control—and such a combination is likely to be very useful. Therefore, development of control algorithms for high-order systems is worthwhile.

As with position control, and using the induction principle, we may define the mnemonicability for a rate system as the coincidence of the directions of the shift vector of the input device and the velocity increment vector of the executing device gripper. We may write this correlation as

$$\Delta \dot{Y}(t) = k(t) \Delta X(t)$$

and after its transformation, we obtain

$$\dot{Y}(t) = \int_{0}^{t} k(t) \dot{X}(t) \, dt, \quad \dot{Y}(0) = 0.$$ \hspace{1cm} (4)

By extending this analogy to the case of acceleration control, mnemonicability may be said to be characterized by the correlation between directions of the input device shift vector and the acceleration increment vector of the executing device gripper. Then, the mnemonicability condition for acceleration control is:

$$\Delta \ddot{Y}(t) = k_A(t) \Delta X(t)$$ \hspace{1cm} (5)

After transformation of expression (5), we get the algorithm

$$\ddot{Y}(t) = \int_{0}^{t} k_A(t) \ddot{X}(t) \, dt, \quad \ddot{Y}(0) = 0.$$ \hspace{1cm} (6)

2.4 Control by Means of Input Device Acceleration

An additional possibility for remote control is suggested when we differentiate the initial expression (2) twice with respect to time. As this takes place, we get

$$\ddot{Y} = k(t) \dot{X}(t) + k(t) \ddot{X}(t)$$ \hspace{1cm} (7)

and by integrating this correlation twice, we get the algorithm

$$Y(t) = \int_{0}^{t} \int_{0}^{t} \left[ k(t) \int_{0}^{t} \dot{X}(t) \, dt + k(t) \ddot{X}(t) \right] \, dt \, dt.$$ \hspace{1cm} (8)

Here, the control is set, not by means of handle position or velocity changing, but by altering the acceleration of the input handle. Acceleration gauges must be used as sensors to give original properties to the hand controller. In this case, the hand controller is not connected to the base, but moves freely in the operator’s hand.

A schematic setup of such an input device is shown in Figure 5. Three accelerometers, \(A_1, A_2,\) and \(A_3,\) are placed here according to three coordinate axis. The device also has a button \(B\) for robot gripper control, and a connection unit \(CU\) that transfers information into the control system. It is clear that such device organization leads to a special control technology and requires corresponding training of the HO. However, the positive advantages of such an approach may be decisive.

The above examples are related to the position [Eq. (8)] and acceleration [Eq. (7)] manipulator control, but it is clear that it is also possible to control manipulator gripper velocity. By differentiating Eq. (8), we get the following algorithm:

$$\ddot{Y}(t) = \int_{0}^{t} \left[ k(t) \int_{0}^{t} \dot{X}(t) \, dt + k(t) \ddot{X}(t) \right] \, dt.$$ \hspace{1cm} (6)

The input device shown in Figure 5 is primarily intended for realization of manipulator transportation motions. The realization of its orientation motions requires the use of either additional sensors or additional programs. As additional sensors, ordinary push-buttons for corresponding DOFs may be used. For practical control purposes, these are usually sufficient because these motions do not normally demand very high accuracy or speed.

If, however, there is such a necessity, handle sensors (Figure 5) may be used. Signals from sensors \(A_1, A_2,\) and \(A_3\) are produced not only during handle linear shift, but also during its rotations about the axes \(x, y, z.\) In fact, under handle rotation about the \(x\) axis, the sensors \(A_2\) and \(A_3\) produce corresponding signals, depending on rotation angle speed. In a similar manner, when the
handle rotates about the y axis, sensors \( A_1 \) and \( A_2 \) work; when the handle rotates about the z axis, sensors \( A_1 \) and \( A_3 \) work. This fact may be used to organize a control system for gripper orientation. There is one difficulty here with the determination of rotation direction, because the sensor signals are not direction dependent. The solution to this problem requires placement of additional simple switchers on the hand controller.

2.5 Automatic Parameter Adjustment

In some forms of telerobotic system work, the flow of information reaching the HO that must be organized using the hand controller exceeds his/her information processing capabilities. In such a case, it is clearly not practical to burden the HO with an additional parameter signal-producing function. This work should therefore be handled by a special automatic device. A simple logical process may serve as the basis of its operation.

Highly precise manipulation is usually realized by an HO using slow, “creep” velocities in all manipulator joints. At the same time, adaptive algorithms are obtained on the assumption that minimum manipulator gain corresponds to maximum positioning accuracy and that maximum gain corresponds to maximum transportation speed. We may then relate each of the shift velocities \( \dot{x}_i, \) \( i = 1, \ldots, n \) (\( n \) is a number of controlled channels) of the input device axis with the manipulator control system gain. For one control channel, the dependence is

\[
k_i(t) = F[|\dot{x}_i|]
\]

and it is more simply realized with the help of a proportional correlation

\[
k_i(t) = k_{\text{min}} + \alpha|\dot{x}_i|, \quad \alpha = \text{const}, \quad k_{\text{min}} = \text{const.} \quad (9)
\]

Here, the value \( k_{\text{min}} \) ensures maximum accuracy of teleoperation.

However, by using dependences (9), we may obtain inequality of different channel gains and, accordingly, mnemonica-bility deterioration. To keep a mnemonica-bility level, it is necessary to ensure the equality of all the gains \( k_i (i = 1, \ldots, n) \).

We may achieve this by using expression (9) in the form

\[
k_i(t) = k_{\text{min}} + \alpha|\dot{x}_i^0(t)| \quad (10)
\]

and by choosing values \( \dot{x}_i^0 \) as one of following kinds:

\[
|\dot{x}_i^0(t)| = \max |\dot{x}_i(t)|, \quad i = 1, \ldots, n; \quad (11)
\]

\[
|\dot{x}_i^0(t)| = \frac{1}{n} \sum_{j=1}^{n} |\dot{x}_j(t)| \quad (12)
\]

Version (11) uses energetic robot possibilities more fully. Maximum values of joint velocities are chosen here based on the considerations discussed below.

For precise task performance, low joint velocities usually occur in all manipulator joints. If a manipulator pro-
duces a fast operation, it may be performed, depending on manipulator structure, with high motion velocity in one (or some) controlled joint(s) and with low velocity in other joints; but in this situation, the shift velocity in the first group of joints should be the maximum that algorithm (11) ensures.

Based on dependencies (2) and (10), a new class of adaptive algorithms can be obtained. The gain adjustment is implemented automatically, according, for instance, to the expression

$$Y(t) = \int_0^t [k_{\text{min}} + \alpha |\mathbf{X}(t)|] \mathbf{X}(t) \, dt \quad (13)$$

where vector $|\mathbf{X}(t)|$ components have been determined, for example, by expression (11).

A special control device, the block diagram of which is shown in Figure 6, corresponds to this version of the adaptive system. New blocks have been used here: $BM_1$, $BM_2$, $BM_n$, $n$ blocks of module acquisition; $DS$, a discriminator of the maximum velocity $max |\dot{x}(t)|$; a summing amplifier $2_1$, the multiplier $M_{1_1}$ and integrator $I_1$ of the $i$th channel.

We see that, in this case, a control of the parameters of the coordinate controller takes place, but not quite a control of object parameters. Note that the automatic parameter adjustment may be realized, not only for a position (13) type system, but also for other types of systems.

3 Adaptive Control Efficiency Study

Adaptive control efficiency testing was realized by means of seminatural simulation and investigation of real industrial robot control.

The block diagram of the experimental setup for seminatural simulation is shown in Figure 7. In the setup an HO-controlled Cartesian two-coordinate-plane manipulator model MM uses a plane input device SD to set control signals. These signals enter the MM through an analog computer AC, in which the control algorithms are implemented. The use of AC in our seminatural simulations stems from our desire to realize the control process in real time.

The scheme of the control system model is shown in Figure 8. It was based on use of operational amplifiers $A_1, \ldots, A_4$. Parameter signal control was set by measuring the squeezing force in handle H (which consisted of two spring-mounted, movable parts with a corresponding potentiometer sensor).

An HO moved a model endpoint (an interchangeable calibrated cylinder) on a trajectory across calibrated holes $H_1, \ldots, H_4$ (Fig. 9) drilled into a transparent plane plate, inserting the cylinder into each of the holes in turn. Each hole was provided with an electrical contact $EC_1, \ldots, EC_4$. When the cylinder entered the hole, an automatic device AD (Figure 7) produced an impulse that switched on a lamp, permitting the HO to move on to the next hole. This task was based on the typical “peg-in-hole” operation applied previously to solve
many robotic test problems (for example, in Hannaford et al., 1991).

The overall cycle consisted of three shifts (transportation task) and three cylinder guidances to the target (positioning task). The AD (Figure 7) switched the AC on and off and also the clock that fixed the full time $T_0$ operation. So, with the help of the unit, a sequence of three tasks was simulated, each of which consisted of the fast transportation of an executing organ to a working point, followed by the fulfillment of a precise assembly operation.

During the experiment, three operators (males) without any skills in remote manipulation were trained to work on the unit with calibrated cylinders of different diameters (8.0; 9.0; 9.4; 9.8 mm) and holes of 10 mm diameter. After the training stage, which involved performing the three-sequence task 10 times, each operator carried out 20 tasks for each type of studied control system:

1—position coordinate system (3);
2—position adaptive system (2);
3—rate adaptive system (4).

It is obvious that system characteristics essentially depend on the choice of parameters for each kind of system. Therefore, the position coordinate system gain was set at a minimum $k = 1$, permitting us to realize the necessary precision while reaching all points of a given working area of the manipulator model. The adaptive rate system gain was also chosen through consideration of the needed precision and the possibility of its techni-
realization (0.1 ≤ k_R ≤ 1.0). The same considerations were used to determine the adaptive position system gain (0.5 ≤ k ≤ 5.0).

All experimental data were statistically processed, and average values for one of the operators are presented in Figure 10. The graph abscissa is a parameter \( v = \delta/S \), where \( \delta \) is the clearance that equals the difference between the hole diameter and the diameter of the calibrated cylinder inserted by the manipulator model into the hole, and \( S \) is the maximum distance of manipulator gripper shift between positioning points. Parameters \( S \) and \( \delta \) are always taken into account in telerobotics (Ver- tut and Coiffet, 1985) but they are usually considered in isolation. The index \( v \) represents the generalized characteristic that accounts for different kinds of tasks performed by the manipulator. In the investigations, this index had the minimum value 0.58 · 10⁻². The adaptive position system quality index was found to outperform the same index of the coordinate system by 15%. This result indicates that despite the comparatively small depths of gain control, considerable improvement of operator-manipulator system quality was revealed for the adaptive position system under accuracy allowance decrease.

For actual robotic systems, value \( S \) principally coincides with workspace dimensions and index \( \delta \) has a value of the same real order. Thus, for these systems, index \( v \) value is almost always smaller than the above calculated values. Real telerobot operation characteristics will always be situated more to the left of the points showed in Figure 10, which indicates an increase of real adaptive control efficiency.

Lastly, the dependencies of Figure 10 indicate that parameter control does not make the rate system sufficiently effective in comparison to the other investigated systems. This leads to the conclusion that the use of such a system for precise task fulfillment is not worthwhile.

The elaboration of remote control systems for real industrial robot teaching was also performed when the author worked in the Kazakh State University (Alma- Ata, the former USSR). One of these systems (Figure 11) was tested to control a cylinder-type industrial robot. Correction depths of the system gain equal to 32 db were obtained. The test was carried out under the control of robot rotation motion (Figure 12) when the motion duration from an initial point \( A \) to a target point \( P \) was fixed.

The following average indices of positioning accuracy were obtained as the result of 10 operations for regimes: ordinary position control on algorithm (3)—2.3° position adaptive control on algorithm (2)—7.5°

It can be seen that control accuracy using the adaptive control system was more than 15 times greater than when using ordinary coordinate control. These results confirm the inference gained from seminatural simulation (see Section 3 above) that adaptive control efficiency increases when real teleoperations are performed.
the organization of a sufficiently effective control process over equipment.

All algorithms obtained by us are shown together in Table 1, in which conventional coordinate algorithms are also presented for those cases when \( k = \text{const} \). Conventional algorithms have a traditional form that confirms our assumptions based on the mnemonicability notion used when obtaining adaptive algorithms.

Developed adaptive algorithms may be used depending on work conditions and on the purposes of a teleoperation system. For instance, based on adaptive algorithms, position-force hybrid systems may be organized.

Remote adaptive system varieties have been proposed that are based either on manual production of the parameter signal, or on automatic production in connection with changes in the coordinate control signal. The latter version is less flexible, but it ensures less information loading on the HO.

A remote control with parameter adaptation permits increased control system resolution up to the maximum accuracy of position systems; at the same time, it ensures the maximum speed that characterizes rate systems.

Adaptive algorithms permit both analog and digital realization; in addition, the former is performed very simply and problems that occur with real-time control do not arise. In addition, adaptive algorithms are very simple as compared to the combined systems of position-rate control (Medvedev, Leskov, and Yushchenko, 1978; Melton, Rose, and Hedin, 1971) that have the same purpose. Because of these factors, adaptive systems enjoy lower cost and higher reliability.

Method efficiency was experimentally shown by using seminatural simulation and investigation of real industrial robot control. In the simulations, the performed task was, in fact, similar to one of those used by Hanaford and others (Hanaford et al., 1991). The only difference was that they used their peg-in-hole task primarily to study force interactions during insertion/extraction operations. They, therefore, ignored a translation component, which was a principal part of our investigation. In our study, this component was increased to require more flexible and versatile telerobot qualities, such as accuracy and fast operation. An approach utility with gain automatic tuning was demon-

Figure 12. Layout for testing an industrial robot remote control system.

4 Discussion and Conclusion

Flexible alteration of object parameters provides new possibilities for the development of different kinds of effective robots. In principle, the approach is related to gain adjustment, for instance, adjustable scaling—not only related to displacements from master to slave and forces from slave to master (Salcudean and Yan, 1994), but also to power and impedance in bilateral manipulators (Colgate, 1991), as are discussed in present-day publications. A scaling change through change in gain while the HO is working with master-slave systems (Sae-nger and Pegden, 1973) is usually realized by switching, a process that poses challenges for the HO. In adaptive CPC systems, these problems practically disappear because the transition process from one value of the gain to another is continuous.

Based on the mnemonicability notion use for system synthesis, flexible alteration of object parameters allows the organization of the adaptive control of robot gripper position, velocity, and acceleration through the use of controlled signals of position, velocity, and acceleration of the input handle. In the last case, the HO is not limited to a certain place, and he/she can move to any location within the workplace. The problem was also discussed in papers (Von Hinuber and Janocha, 1993; Weck and Lauffs, 1987) that relate to practical instances. The proposed approach permits this problem to be solved in the context of the adaptive control and permits
Table 1. Algorithms of Coordinate-Parameter Control (CPC) and Coordinate Control (CC) for One Controlled Channel

<table>
<thead>
<tr>
<th>Input Signal</th>
<th>Position Control</th>
<th>Velocity Control</th>
<th>Acceleration Control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CPC (k = var)</strong></td>
<td>( y = \int k(t) \frac{d}{dt} x(t) , dt )</td>
<td>( \dot{y} = \int k(t) \frac{d}{dt} \dot{x}(t) , dt )</td>
<td>( \ddot{y} = \int k(t) \frac{d}{dt} \ddot{x}(t) , dt )</td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>( y = \int k(t) \dot{x}(t) , dt )</td>
<td>( \dot{y} = \int k(t) \dot{x}(t) , dt )</td>
<td>( \ddot{y} = k(t) \dot{x}(t) )</td>
</tr>
<tr>
<td>Acceleration</td>
<td>( y = \int \int [k \dddot{x} + k \dot{x} , dt] , dt )</td>
<td>( \dot{y} = \int \int [k \dddot{x} + k \dot{x} , dt] , dt )</td>
<td>( \ddot{y} = k(t) \dot{x}(t) + \dot{k}(t) \dot{x}(t) , dt )</td>
</tr>
<tr>
<td><strong>CC (k = const)</strong></td>
<td>( y = kx )</td>
<td>( \dot{y} = k \dot{x} )</td>
<td>( \ddot{y} = k \dddot{x} )</td>
</tr>
<tr>
<td>Position</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity</td>
<td>( y = k \int \dot{x} , dt )</td>
<td>( \dot{y} = k \int \dot{x} , dt )</td>
<td>( \ddot{y} = k \dddot{x} )</td>
</tr>
<tr>
<td>Acceleration</td>
<td>( y = k \int \int \dddot{x} , dt , dt )</td>
<td>( \dot{y} = k \int \int \dddot{x} , dt , dt )</td>
<td>( \ddot{y} = k \dddot{x} )</td>
</tr>
</tbody>
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strated in another closely related study and presented in (Gurevich, Slutski, and Edan, 1995; Slutski, Gurevich, and Edan, 1997). Both our simulation and real testing results indicated a considerable increase of telecontrol quality while using the adaptive control method. As for acceleration control, a similar approach was recently tested in the context of coordinate control with an elaboration of the 6D control device (A Flock of Birds) of the Ascension Technology Corporation that was used in experiments described in Nechypor and Xu, 1995.

Lastly, it should be noted that the described research is, in fact, only the first stage of method development. A number of questions exist to which answers have not yet been found: for example, a stability problem may occur in these systems. In our investigation, this problem was solved experimentally, by choosing the limits of the coefficients \( k(t) \) in algorithms (2) and (4), because these coefficients specifically influence system stability. The same approach was used in studying the algorithm with automatic gain adjustment, as described in our papers (Gurevich, Slutski, and Edan, 1995; Slutski, Gurevich, and Edan, 1997). In this case, a parameter (13) was limited in order to remove the danger of instability in the system. However, the proper resolution of this problem awaits further consideration. Another subject for future investigation is the justification and choice of the most suitable adaptive algorithm for implementation in different industrial applications.

Summing up, the distribution of functions between control channels in the adaptive system is as 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. The parameter control circuit is used to improve (optimize) the control process quality indices.

The manipulator gain adaptation may play the same role in remote semiautomatic control as the impedance adjustment in master-slave systems. Sheridan (1992) says that this “may be a promising way of making a master-slave teleoperator more versatile.” Mention of such adjustment was also made by Vertut and Coiffet (1985). Therefore, there is reason to hope that the results of the present study will help in the development of ideas for semiautomatic control systems.

The adaptive CPC method also represents a rather common approach for automatic machine control problem solving, but its use in telerobotic systems is now more advanced in comparison to other applications of the method. It indicates that there are good prospects to develop this approach for advanced teleoperation sys-
tems (Bejczy, 1994; Fiorini, Bejczy, and Schenker, 1993; Hirzinger, 1993) and other present-day machines controlled by the HO.

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