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ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, **57**
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Procedure for the Design of Mechanical Systems of Mobile Self-Programming Robot-Technical Complexes

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1. Introduction

1.1. Characteristics of existing design methods for robots

Using the classical methods for designing mechanical system inevitably leads to difficulties with the increase of the number of degrees of freedom. Usually, the classical methods give an ideal possibility for the dimensioning of mechanical systems with up to 6 degrees of freedom. Using the capabilities of the modern computer facilities it becomes possible to dimension mechanical systems of up to 16-20 degrees of freedom. However, this is not enough when speaking about the mechanical system of Mobile Self-Programming Robot-Technical Complexes. The degrees of freedom are much more in these mechanical systems (about 100, 200, and in some cases they may exceed even 1000).

1.2. Need for Mobile Self-Programming Robot-Technical Complexes

Existing wheel transport needs roads that have certain smoothness in order to provide smooth and fast motion for the transport means. Undoubtedly, the wheel transport is irreplaceable for smooth roads and highways. Some grounds exist (Fig.1), however, where it is very difficult or impossible to construct roads that are suitable for wheel transport. Irreplaceable for such areas at this stage is the walking method of transportation.

Mechanical systems which can carry out walking transportation activity require many degrees of freedom. These degrees of freedom are imposed by the walking method of movement itself and the kinematic dampening of shocks and shock states of the mechanical system in particular sections as well as the designation of the Mobile Self-Programming Robot-Technical Complexes.

Fig. 1. Areas without roads

2. Task

A procedure needs to be made for designing mechanical systems of the long kinematic chains with many degrees of freedom that are intended for Mobile Self-Programming Robot-Technical Complexes.

3. Route, path, gait

A route is a conical-cylindrical space or band of the place of existence of Mobile Self-Programming Robot-Technical Complexes that connects two sites (Fig. 2).

A path is a characteristic of the impact of Mobile Self-Programming Robot-Technical Complexes on the route for carrying out the movement (mobility) from one place to another (Fig. 3).

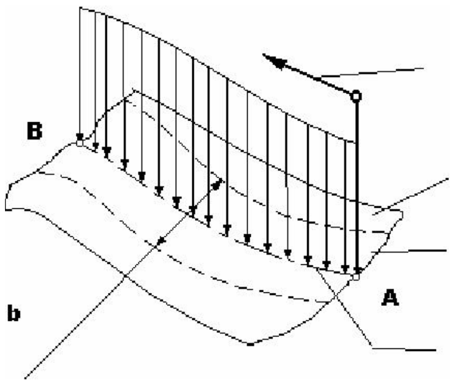


Fig. 2. Route elements

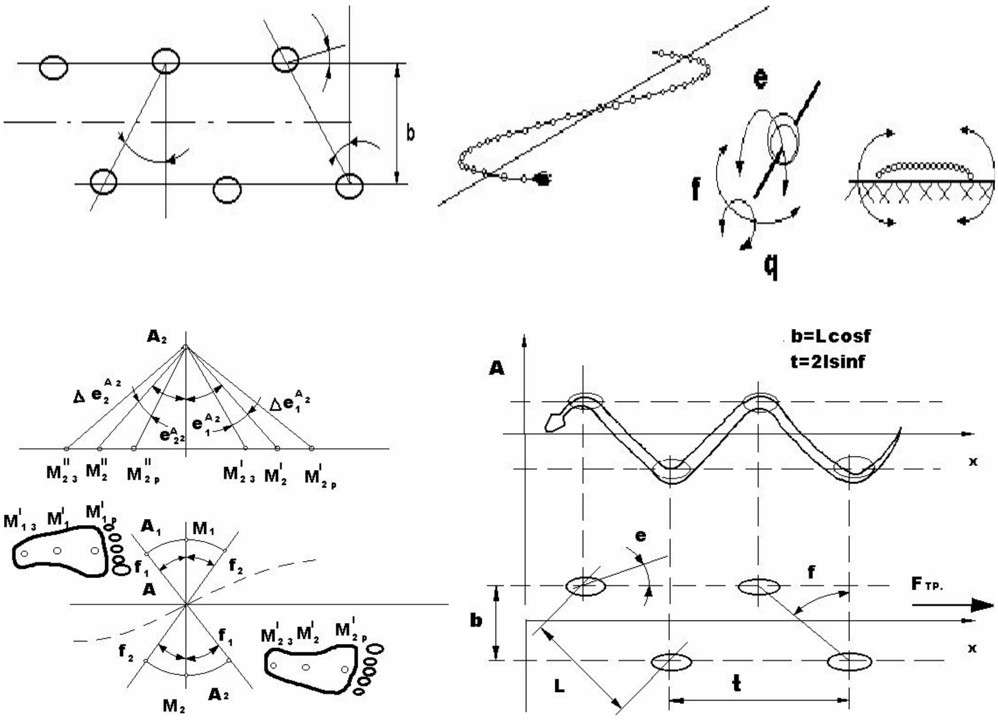
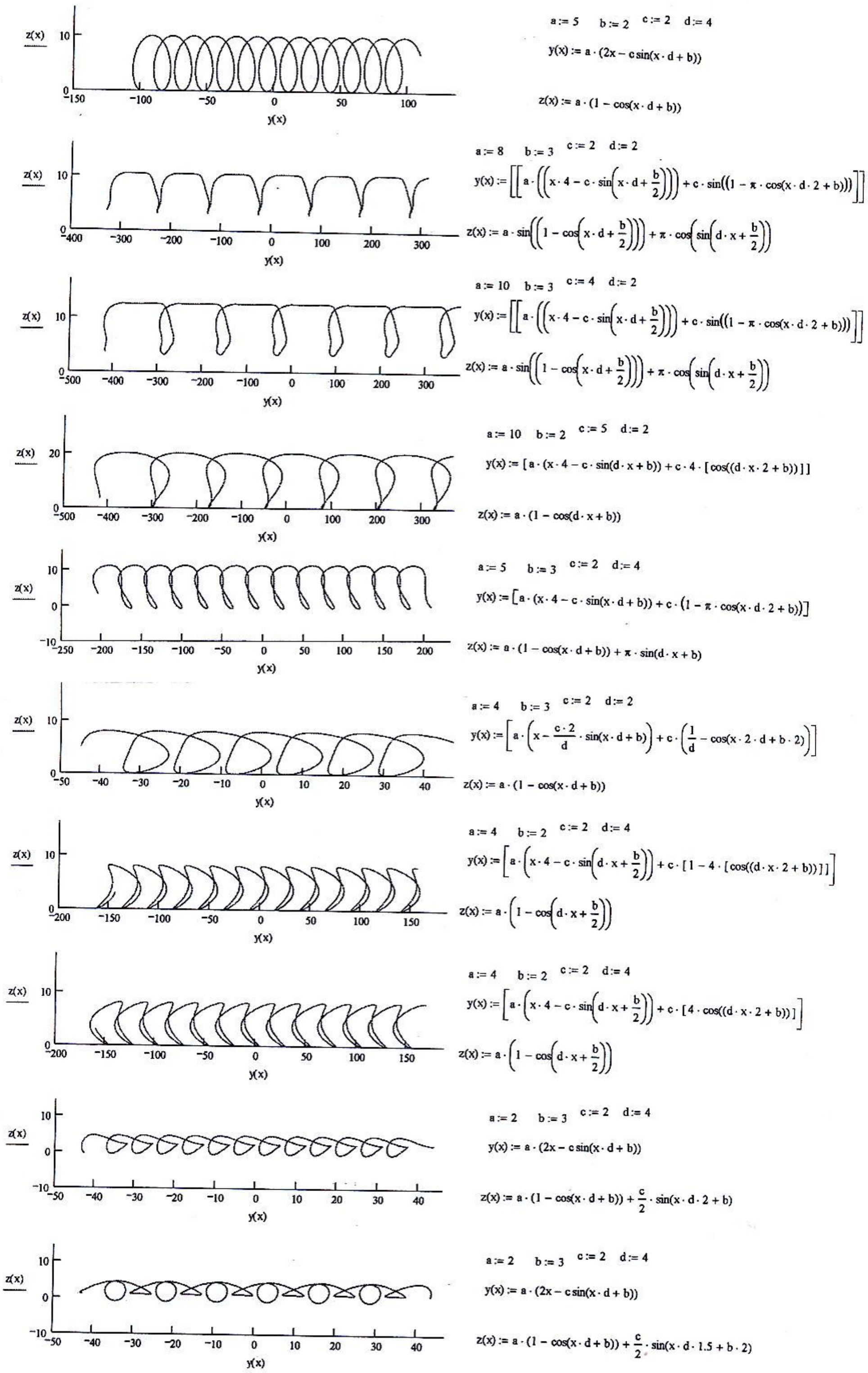


Fig. 3. Sketch of path with steps

Gait is the mechanism (technology) for realization of the movements (Fig. 4). Each gait consists of the following components:

a) locomotoric part;
b) control part;
c) supporting part.



$$a := 5 \quad b := 2 \quad c := 2 \quad d := 4$$
$$y(x) := a \cdot (2x - c\sin(x \cdot d + b))$$
$$z(x) := a \cdot (1 - \cos(x \cdot d + b))$$

$$a := 8 \quad b := 3 \quad c := 2 \quad d := 2$$
$$y(x) := \left[\left[a \cdot \left(\left(x \cdot 4 - c \cdot \sin\left(x \cdot d + \frac{b}{2}\right)\right)\right) + c \cdot \sin((1 - \pi \cdot \cos(x \cdot d \cdot 2 + b)))\right]\right]$$
$$z(x) := a \cdot \sin\left(\left(1 - \cos\left(x \cdot d + \frac{b}{2}\right)\right)\right) + \pi \cdot \cos\left(\sin\left(d \cdot x + \frac{b}{2}\right)\right)$$

$$a := 10 \quad b := 3 \quad c := 4 \quad d := 2$$
$$y(x) := \left[\left[a \cdot \left(\left(x \cdot 4 - c \cdot \sin\left(x \cdot d + \frac{b}{2}\right)\right)\right) + c \cdot \sin((1 - \pi \cdot \cos(x \cdot d \cdot 2 + b)))\right]\right]$$
$$z(x) := a \cdot \sin\left(\left(1 - \cos\left(x \cdot d + \frac{b}{2}\right)\right)\right) + \pi \cdot \cos\left(\sin\left(d \cdot x + \frac{b}{2}\right)\right)$$

$$a := 10 \quad b := 2 \quad c := 5 \quad d := 2$$
$$y(x) := [a \cdot (x \cdot 4 - c \cdot \sin(d \cdot x + b)) + c \cdot 4 \cdot [\cos((d \cdot x \cdot 2 + b))]]$$
$$z(x) := a \cdot (1 - \cos(d \cdot x + b))$$

$$a := 5 \quad b := 3 \quad c := 2 \quad d := 4$$
$$y(x) := [a \cdot (x \cdot 4 - c \cdot \sin(x \cdot d + b)) + c \cdot (1 - \pi \cdot \cos(x \cdot d \cdot 2 + b))]$$
$$z(x) := a \cdot (1 - \cos(x \cdot d + b)) + \pi \cdot \sin(d \cdot x + b)$$

$$a := 4 \quad b := 3 \quad c := 2 \quad d := 2$$
$$y(x) := \left[a \cdot \left(x - \frac{c \cdot 2}{d} \cdot \sin(x \cdot d + b)\right) + c \cdot \left(\frac{1}{d} - \cos(x \cdot 2 \cdot d + b \cdot 2)\right)\right]$$
$$z(x) := a \cdot (1 - \cos(x \cdot d + b))$$

$$a := 4 \quad b := 2 \quad c := 2 \quad d := 4$$
$$y(x) := \left[a \cdot \left(x \cdot 4 - c \cdot \sin\left(d \cdot x + \frac{b}{2}\right)\right) + c \cdot [1 - 4 \cdot [\cos((d \cdot x \cdot 2 + b))]]\right]$$
$$z(x) := a \cdot \left(1 - \cos\left(d \cdot x + \frac{b}{2}\right)\right)$$

$$a := 4 \quad b := 2 \quad c := 2 \quad d := 4$$
$$y(x) := \left[a \cdot \left(x \cdot 4 - c \cdot \sin\left(d \cdot x + \frac{b}{2}\right)\right) + c \cdot [4 \cdot \cos((d \cdot x \cdot 2 + b))]\right]$$
$$z(x) := a \cdot \left(1 - \cos\left(d \cdot x + \frac{b}{2}\right)\right)$$

$$a := 2 \quad b := 3 \quad c := 2 \quad d := 4$$
$$y(x) := a \cdot (2x - c\sin(x \cdot d + b))$$
$$z(x) := a \cdot (1 - \cos(x \cdot d + b)) + \frac{c}{2} \cdot \sin(x \cdot d \cdot 2 + b)$$

$$a := 2 \quad b := 3 \quad c := 2 \quad d := 4$$
$$y(x) := a \cdot (2x - c\sin(x \cdot d + b))$$
$$z(x) := a \cdot (1 - \cos(x \cdot d + b)) + \frac{c}{2} \cdot \sin(x \cdot d \cdot 1.5 + b \cdot 2)$$

Fig. 4. Types of idealized gaits

4. Basic schemes of Mobile Self-Programming Robot-Technical Complexes

The kinematic structures of Mobile Self-Programming Robot-Technical Complexes are long kinematic chains which could be summarized as the following three schemes for plane and space (Sinilkov [15, 16])(Figs. 5 and 6):

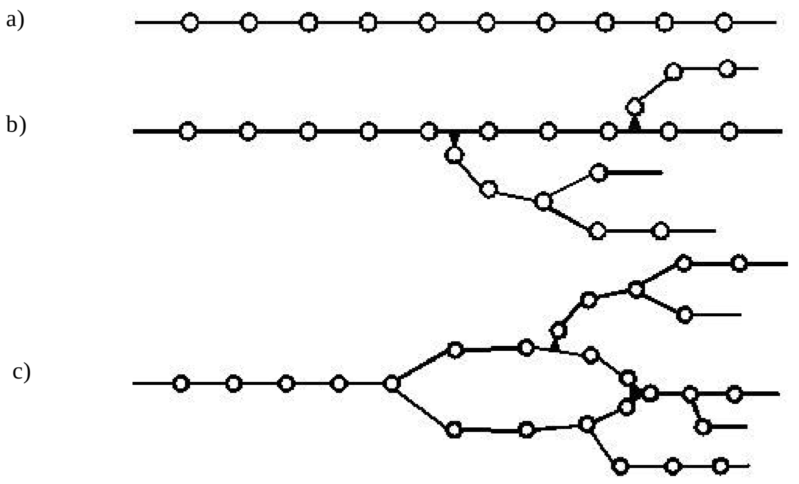


Fig. 5. Basic kinematic schemes

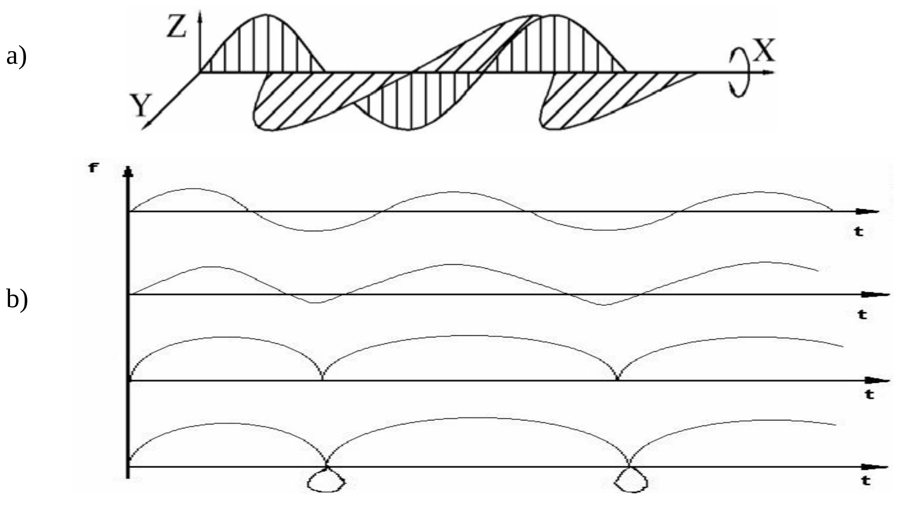


Fig. 6. Laws of motion of the main vertebral structure and the limbs of mobile self-programming robot-technical complexes

The basic schemes could be considered as composed of several elements:

a) axial kinematic chain – there may be one chain or more that work synchronously (Fig. 7); b) connecting mechanisms (Fig. 8); c) peripheral kinematic chains (Figs. 9 and 10).

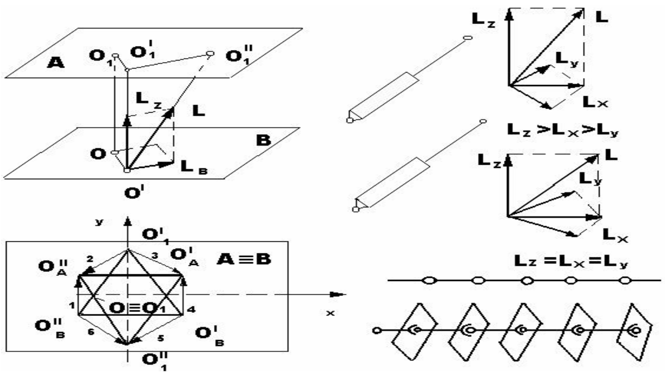


Fig. 7. Axial kinematic chain

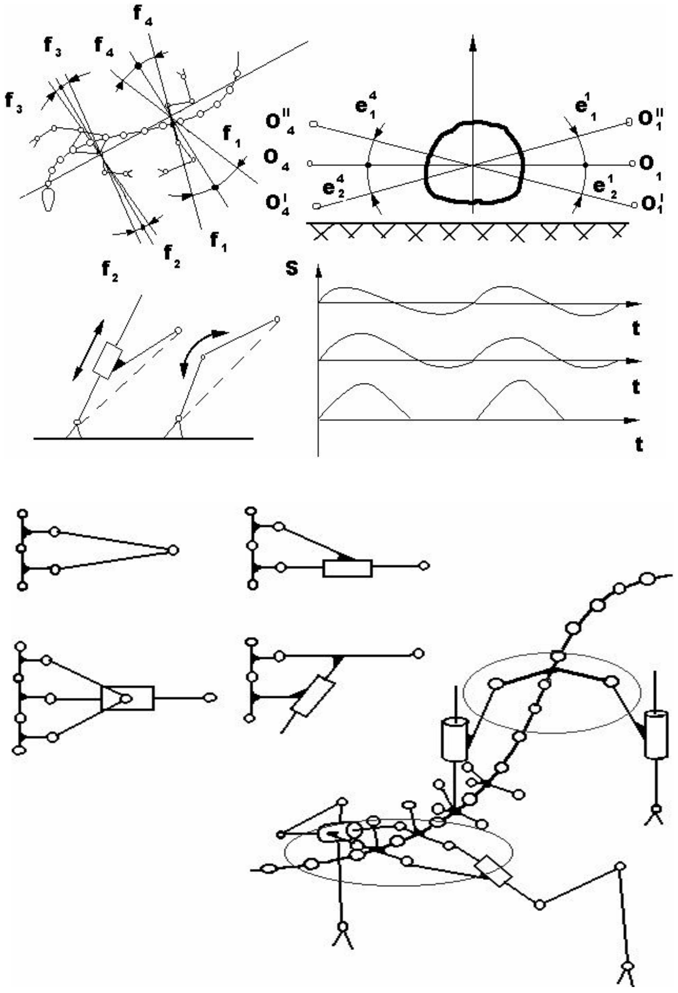


Fig. 8. Connecting mechanisms

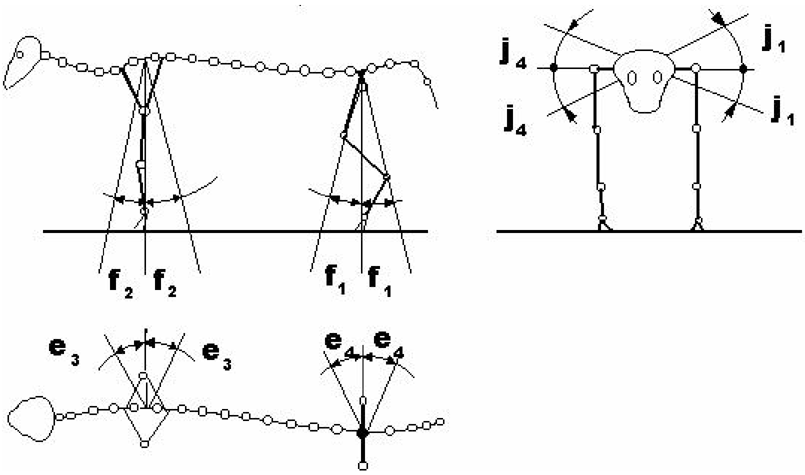


Fig. 9. Peripheral kinematic chains

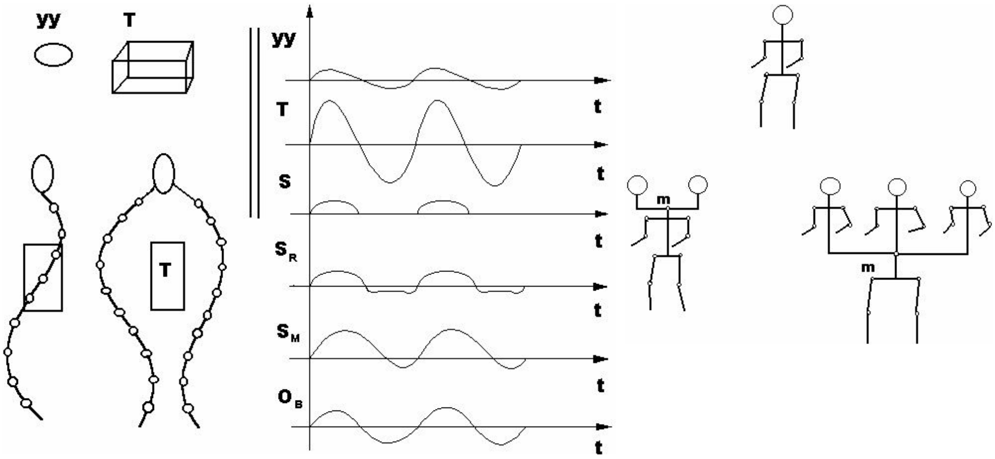


Fig. 10. Mubots

5. Relationship between route, path, gait and the structure of mobile self-programming robot-technical complexes

In the coordinate systems in Fig. 4 an illustration is given of some motions of the individual elements of the basic schemes which can realize those kinematic chains. It is well seen that the axial kinematic chains can perform smooth sinusoidal motions whereas the peripheral kinematic chains can perform a motion which is accompanied by shock states. These motions are particularly suitable for walking gaits shown in item 3 for the realization of movement on the track by the Mobile Self-Programming Robot-Technical Complexes between the two sites.

6. Types of motions needed for Mobile Self-Programming Robot-Technical Complexes

Transport motions are not the only motions which the mechanical system of Mobile Self-Programming Robot-Technical Complexes has to perform.

6.1. Orientation-related motions

Orientation-related motions should also be added to the main transport motion. I.e., Mobile Self-Programming Robot-Technical Complexes are required to turn, stop, start, accelerate etc.

6.2. Motions related to the technological impact

The mechanical system of Mobile Self-Programming Robot-Technical Complexes is required to perform all motions for which it is designed such as loading, unloading, cargo handling etc.

6.3. Motions related to servicing of own mechanisms

This requirement is connected with the self-repair factor. I.e., the end points of the end mechanisms of the mechanical system should be within their range of accessibility to include the entire mechanical system of the Mobile Self-Programming Robot-Technical Complexes.

6.4. Motions related to the operation of mobile self-programming robot-technical complexes in case of failure

These motions and their related additional degrees of freedom in the mechanical system are described in item 10.

By summing all these motions we can obtain the global motion which the mechanical system of the mobile self-programming robot-technical complexes needs to perform. These motions provide the abilities the mobile self-programming robot-technical complex will have, and also impose a certain number of degrees of freedom on its mechanical system.

7. Primal and inverse problems of kinematics

7.1. The primal problem

As initial data for solving the primal problem we take the possible motions of the axial kinematic chains, in particular – the mobile motion of preset gait types. The primal problem is not connected with setting movements of the driving mechanisms as initial data, but with a smooth, cyclic, uniform motion of the axial kinematic chain. This does not mean that those movements cover the full range of possible motions of the axial kinematic chain. They are only a part of the possible motions of the axial kinematic chain; however they are enough to realize the preset gait types. We try to find the type of movement at the end of branching of the long kinematic chain, i.e. the motion of the axial kinematic chain might be of the following type:

$$(1)\qquad \left| \begin{array}{l} f_1 = f_1(x_1, y_1, z_1, t) \\ f_2 = f_2(x_2, y_2, z_2, t) \\ \qquad\quad \cdots \\ f_n = f_n(x_n, y_n, z_n, t), \end{array} \right.$$

where n is the number of axial kinematic chains within the long kinematic chain discussed.

Then, by using the transformation functions:

$$(2)\qquad \left| \begin{array}{l} \psi_1 = \psi_1(x_1, y_1, z_1, \alpha_1, \beta_1, \gamma_1, t) + \sum_{i=1}^{p} r_{1i}(u_1, v_1, w_1, \omega_1, \varepsilon_1, \eta_1, t) \\ \psi_2 = \psi_2(x_2, y_2, z_2, \alpha_2, \beta_2, \gamma_2, t) + \sum_{i=1}^{p} r_{2i}(u_2, v_2, w_2, \omega_2, \varepsilon_2, \eta_2, t) \\ \qquad\qquad\qquad\qquad \cdots \\ \psi_m = \psi_m(x_m, y_m, z_m, \alpha_m, \beta_m, \gamma_m, t) + \sum_{i=1}^{p} r_{mi}(u_m, v_m, w_m, \omega_m, \varepsilon_m, \eta_m, t), \end{array} \right.$$

where m is the number of branches or closed loops, and p is the number of relative motions performed by the engines of the respective mechanisms, which are directly connected with the axial kinematic chain or so-called connecting mechanisms (Sinilkov [15]; Jenta [3]; Iliev [6]; Kolovskij, Slousht [9]). The movement is transformed to:

$$(3)\qquad \left| \begin{array}{l} \varphi_1 = \varphi_1(x_1^t, y_1^t, z_1^t, \alpha_1^t, \beta_1^t, \gamma_1^t, t) \\ \varphi_2 = \varphi_2(x_2^t, y_2^t, z_2^t, \alpha_2^t, \beta_2^t, \gamma_2^t, t) \\ \qquad\qquad \cdots \\ \varphi_m = \varphi_m(x_m^t, y_m^t, z_m^t, \alpha_m^t, \beta_m^t, \gamma_m^t, t). \end{array} \right.$$

This scheme is repeated for the next mechanism towards the periphery and so on, until the end of branching is reached.

This computational scheme is repeated for each branching towards the periphery.

Then the following is added to the mobile motion:

1) the movement for technological impact on objects of the environment;
2) the movement for orientation;
3) the movement for servicing the own mechanisms (having in mind the following: each point of each link of the long kinematic chain should be accessible by at least one point of end link of a branching).

The thereby obtained global movement of the long kinematic chain requires a consecutive recalculation according to the computational scheme specified.

7.2. The inverse problem

The reverse order is followed in solving the inverse problem. We set the movement of the end links, i.e. the periphery of the long kinematic chain, and try to find the most appropriate movement of the axial kinematic chain.

The movements (3), which the end links perform, are usually cyclic. They are taken from the gait type, which is to be performed by the Mobile Self-Programming Robot-Technical Complex for the respective road type (Sinilkov [15]; Young John [7]; Koziryov [8]; Kolovskij, Slousht [9]).

The inverse problem has for an object to expand those movements to components, by which we could synthesize known mechanisms and thereby construct the complete long kinematic chain.

Expansion of the movements (3) can be done in various manners:

1) by subtraction of known movements corresponding to respective mechanisms, which are kept in database;

2) by using the Fourier method;

3) by means of spline-functions for expansion of the movements (3 of limited number of movements.

It is compulsory in each subtraction of a known movement from the movements (3) that an examination of the function is made in order to determine its direction of smoothing. This is intended to achieve a motion that is smooth, cyclic and uniform.

The first movement, which we “pick” from the movements (3), is the relative motion of the first mechanism from the periphery to the axial kinematic chain.

$$\upsilon_1 = \upsilon_1(u_1, v_1, w_1, \alpha_1, \beta_1, \gamma_1, t). \tag{4}$$

By using this function we synthesize multitude mechanisms according to the methods of synthesis already known. Those mechanisms normally are in contact with the support at one or more points. Releasing the mechanism from the support at a later stage will lead to the introduction of the transferring component.

One mechanism is selected from the multitude possible mechanisms according to criteria, which are not discussed in this publication.

We subtract (3) from (4) and subtract again a known movement, then we examine the function again. The new known movement also has a relative motion of the type (4). We process it accordingly while having in mind that the output of the first mechanism is the inlet of the second mechanism.

An important feature is that the support of the first mechanism and the support of the second mechanism are not the same link, i.e. a relative motion exists between them.

We proceed in this manner until we reach a mechanism, which output link needs to be set in uniform and cyclic or uniform circular movement. Then we say that this link is a link of an axial kinetic chain of the branching demanded or closed loop of the long kinematic chain.

Supports of the so-synthesized mechanisms are released by synthesizing mechanisms in reverse order, starting from the reached link of axial kinematic chain towards the periphery of the long kinematic chain. Each branching of a long kinematic chain is processed in a similar manner.

Finally we synthesize the mechanism of the axial kinematic chain, which should be capable of performing the uniform cyclic motions around the basic axis.

Depending on the obtained uniform motions of the branches, we can have several axial kinematic chains, which can have serial links (Fig. 3a) or closed loops included (Fig. 3b).

8. Force analysis

The method of force analysis of the mechanical system of a Mobile Self-Programming Robot-Technical Complex does not significantly differ from the method of force analysis of the traditional robottechnical systems.

The transformation functions known from the solution of the kinematic problem can transform the initial loading to each joint in each position and thereby the dimensioning of each link is enabled.

9. Force-kinematic analysis

The force-kinematic analysis is that important and optimizing element of designing Mobile Self-Programming Robot-Technical Complexes, which provides the selection of the effectors in the mechanical system of a Mobile Self-Programming Robot-Technical Complex. By using the whole range of mechanism types – band, cam, toothed, lever and wedge type – it estimated where, in which sections of the mechanical system the use of one or another mechanism is appropriate. In addition, at this stage we can see which link is suitable to have a zero mass and thereby incorporate two adjacent links in one link of more degrees of freedom and others.

10. Emergency operation of a Mobile Self-Programming Robot-Technical Complex

This stage of design of the mechanical system of the Mobile Self-Programming Robot-Technical Complexes is basically an estimate and, possibly, a modification of the mechanical system in order to cover a wider range of failures that would put the Mobile Self-Programming Robot-Technical Complex out of service.

10.1. Replacement of the bushing system of joints with cams

This is associated with the ability of a given joint to function or return by itself into the functional condition if it has been impacted by a force that is beyond the rated range.

This is the so called dislocation of joint with the living organisms.

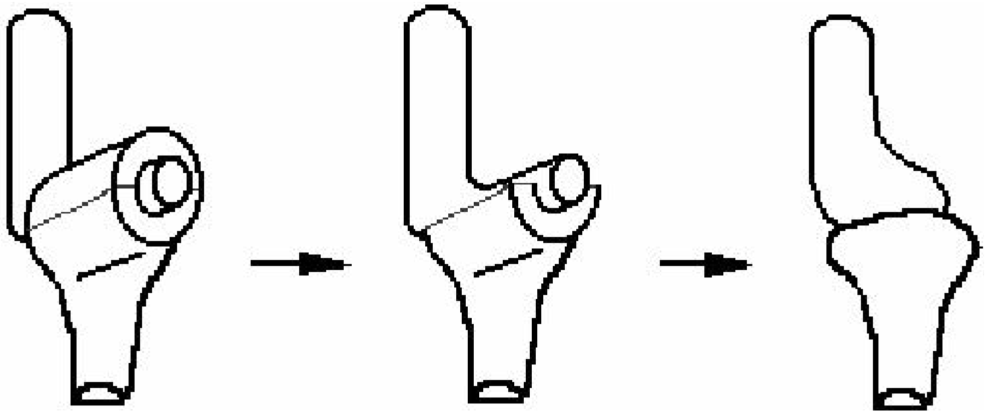


Fig. 11. Modification of the bushing system

10.2. Emergency operation in case of link breakage or engine failure

In case of link breakage or engine failure we have an emergency that restricts the motion of the mechanical system. Possible effects in these cases are:

- a change in the gait type;
- a change in the path type;
- a restriction to the processing motions;
- a change in the possibilities for orientation.

An estimate on these failures enable us to assess the extent of emergency where a Mobile Self-Programming Robot-Technical Complex is able to function.

10.3. The self-repair factor

The self-repair factor gives us an impartial assessment of the extent, to which the mechanical system is capable of performing motions that could be used for self-repair, readjustment or self-service. The requirement is that the end points of the peripheral kinematic chains are able to reach each point of the entire mechanical system of the Mobile Self-Programming Robot-Technical Complex.

This requirement enables the Mobile Self-Programming Robot-Technical Complex to repair minor failures or readjust some of its mechanisms. This makes it possible to extend the life of the mechatronic product called Mobile Self-Programming Robot-Technical Complex.

11. Changeability

If we take into account all possible motions that are required for the future Mobile Self-Programming Robot-Technical Complex, then the number of degrees of freedom in its mechanical system will extraordinarily increase. Say, in the beginning of the designing activity the mobile motion could be realized as a “turtle” type Mobile Self-Programming Robot-Technical Complex, i.e. with solid body and movable limbs. After adding all motions, however, we could find out that we need a flexible body, i.e. an axial kinematic chain.

More possibilities for realization are considered in designing a Mobile Self-Programming Robot-Technical Complex than above. The fact is considered that a machine could perform more than one kind of activity, i.e. we speak about a complex of possibilities.

This possibility for adapting the mechanical system to the function assigned is called changeability and it is set already in the design of the mechanical system of the Mobile Self-Programming Robot-Technical Complex with respect to its kind and limits. The changeability additionally increases the number of degrees of freedom in the mechanical system of the Mobile Self-Programming Robot-Technical Complex.

12. Conclusions

1. The so-presented procedure for the design of mechanical systems of Mobile Self-Programming Robot-Technical Complexes enable us to easily operate those mechanical systems. The use of curves of motion in the mechanics without interpolation of motions reduces the problem of operation to an analogue problem that is far below the capabilities of the modern computers.

2. The so-presented procedure enable us to systemize synchronize the motions of the individual links and mechanisms.

3. The so-presented procedure enable us to design mubots which mechanical systems have no analogy in the animate nature.

4. This procedure is unique in that that in the beginning the designer cannot exactly know the type and number of degrees of freedom of the Mobile Self-Programming Robot-Technical Complex to be designed. Clear and exact criteria are used in the progress of the design process that determine both the type of mechanism to be used, and the type of joint to be applied as well as the type of Mobile Self-Programming Robot-Technical Complex to be created .

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Метод для проектирования механических систем для мобильных самопрограммируемых роботехнических комплексов (МСРК)

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МСРК – это мехатронные изделия, механическая система которых характеризуется с большим количеством степени свободы (больше чем 100). Этот метод дает новый взгляд для проектирования долгих кинематических цепей (ДКЦ) с большой степенью свободы, а также и подходящей вычислительной схемы, предоставляющей возможность для небольшого машинного времени.