Ph.D. Thesis

Methods of increasing the reliability of mechanical grippers

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**Introduction**

Robotisation of production processes is a way of automatisation, which is based on the usage of robots in industrial processes.

Robotisation is the next step in production evolution after automatisation, because the usage of robots gives a possibility to automate different processes, automatisation of which by another ways is inexpedient.

The target of robotisation is increasing technical and economic characteristics of production processes.

Grippers are one of the main parts of the robots, which are used for grasping and holding of manipulated workpieces and technological equipment. Such objects are called the objects of manipulation.

Grippers connect robots with a working space. A gripper is one of the elements that define technical possibility of the robot.

Objects of manipulation can have different dimensions, form, mass etc. It means that for manipulation of different types of objects it is necessary to use different grippers. That is why a gripper is changeable equipment.

Schemes of the grasp depend on requirement specifications and robot possibilities. Those schemes are similar to the grasping schemes of human hand.

Optimisation of robot control is one of the main tasks for creating new production units and adapting the old ones for making new products. Optimal grippers selection according to the requirements of technological process and increasing the reliability of their work is one of the main tasks of robot control optimisation. Those tasks have the particular urgency today in the case of creation different robotised productions, assembling and disassembling operations, realisation of robot control in extreme situations and in the space.
Chapter 1. Workpiece classifications, classifications of the grippers and their elements

Before studying possible ways of increasing quality of grasp it is necessary to analyse main classifications of grippers and their elements and classifications of the workpiece, which can be processed on robotised productions. Let’s start from classification of workpieces.

1.1. Analysing and classifications of workpieces, which can be processed on robotised productions

On robotised production different types of workpieces are machining. The range of such workpieces are defined by the following factors [1]:

1) Constructive parameters of grasped workpieces (geometry and relative position of their parts);
2) Type and condition of the workpiece;
3) Overall dimensions and mass of the workpieces.

Workpieces of one class should have similarly situated surfaces of basing and grasping. These surfaces should be of one type. It is necessary to set up the workpieces without additional calibration, i.e.:

1) Such workpieces should have salient basing surfaces witch can be used for the workpiece orientation in the gripper;
2) The workpieces should be suitable for applying the process of unification and grouped-frequency basis of equipment.

On this ground the classification of workpieces, which can be processing in the robotised systems, is following:

1) Smooth and multidiameter shafts with diameter range from 160 mm to 2000 mm, discs, flanges, rings, cylinders and bushes with diameter up to 500 mm and length up to 300 mm;
2) Plane and three-dimensional workpieces of simple forms (bars, caps, angle bars, workpieces of box-type etc.).

Robots expediency to use for workpieces manipulation from 1 to 500 kg. For workpieces with bigger mass it is necessary to use new special types of robots.

In the case of more detail investigation it is necessary to check the following characteristics of plane surface workpieces, which can be machining on robotised production [2] Table 1.1. In Table 1.1 methods of description for these surfaces are given too.
Table 1.1.

<table>
<thead>
<tr>
<th>Surfaces of plane type workpieces</th>
<th>Method of description for this surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square box</td>
<td>By straight lines situated in a certain way in the space</td>
</tr>
<tr>
<td>Rectangular box</td>
<td>By circle or circles, which are limited in the space by some functions</td>
</tr>
<tr>
<td>Parallelogram</td>
<td></td>
</tr>
<tr>
<td>Triangle</td>
<td></td>
</tr>
<tr>
<td>Trapezium</td>
<td></td>
</tr>
<tr>
<td>Hexagon</td>
<td></td>
</tr>
<tr>
<td>Regular polygon</td>
<td></td>
</tr>
<tr>
<td>Circle</td>
<td></td>
</tr>
<tr>
<td>Semi-circle</td>
<td></td>
</tr>
<tr>
<td>Sector</td>
<td></td>
</tr>
<tr>
<td>Segment</td>
<td></td>
</tr>
<tr>
<td>Ring</td>
<td></td>
</tr>
<tr>
<td>Workpieces of complex forms</td>
<td>By different curves</td>
</tr>
</tbody>
</table>

Thus it is possible to mark out the following form of 3-D objects and types of description their surfaces (Table 1.2).

Table 1.2.

<table>
<thead>
<tr>
<th>Type of 3-D surface</th>
<th>Method of description for this surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder</td>
<td>By lines and circles</td>
</tr>
<tr>
<td>Pyramid</td>
<td>By family of lines</td>
</tr>
<tr>
<td>Hollow cylinder</td>
<td>By family of lines and circles</td>
</tr>
<tr>
<td>Slantwise-cutted cylinder</td>
<td>By family of lines and circles</td>
</tr>
<tr>
<td>Sphere</td>
<td>By family of circles</td>
</tr>
<tr>
<td>Sector of a sphere</td>
<td>By family of lines and circles</td>
</tr>
<tr>
<td>Segment of a sphere</td>
<td>By family of lines and circles</td>
</tr>
<tr>
<td>Cone</td>
<td>By family of lines and circles</td>
</tr>
<tr>
<td>Truncated pyramid</td>
<td>By family of lines</td>
</tr>
<tr>
<td>Truncated cone</td>
<td>By family of circles or lines and circles</td>
</tr>
<tr>
<td>Tore</td>
<td>By family of circles</td>
</tr>
<tr>
<td>Workpieces of difficult forms</td>
<td>By family of lines, circles and curves of difficult forms</td>
</tr>
</tbody>
</table>

The analyses of those tables and literature [3] make it possible to conclude that the main characteristics of manipulated object classification are:

1) Physical condition of workpiece;
2) Form of workpiece;
3) Characteristics of workpiece symmetry;
4) Mobility and orientation of the workpiece in the grasping moment.

According to the physical condition the workpieces are divided into:

1) Liquid workpieces;
2) Granular workpieces
3) Solids workpieces
Usually in robotised production the workpieces are solid and rigid but generally they can be elastic, brittle or plastic too.

Solids are such objects, which in reasonable limits don’t need to limit the maximal application of stress load.

Rigid are such objects, witch deformation during grasping process is neglected small.

This classification in some situation can be extended.

The following factors have big importance for grasping and holding tasks:
1) form of the workpiece surface, which use for grasping process;
2) existence of points, lines and planes of workpiece symmetry;
3) dispensing of inertial characteristics on the workpiece axis.

For workpieces of difficult forms are important to know existence of holes, prominent parts, fin etc.

For the right grasp it is necessary to know the object mobility in the clamping moment (fixed or moving the workpiece on the conveyer, for example).

It is possible, that in the moment of grasp the object is fixed in the special clamping devices or have movement possibility on some directions (for example when the workpiece is situated on the plane or in the jacks, polarizing slot etc).

Number of quantitative characteristics for objects of different classification groups are formed on the base of following factors:
1) overall dimensions of workpiece;
2) position and orientation of their typical axis, lines etc;
3) range of changing forms and position error of workpiece parts;
4) range of workpiece position error changing;
5) mass and other inertial characteristics;
6) permissible values of contact forces.

For each concrete situation this list can be extended.

In the case of requirements statement to the type and method of grasp it is necessary to determine the follow characteristics:
1) direction of grasping movement of the gripper to the workpiece;
2) select surfaces of the workpiece, which is used for grasping process;
3) select the type of grasp.

For applying batch process and using one type of equipment all workpieces, which can be machining on robotised workshops, can be classified by the following characteristics [4]:
1) by constructively-technological analogy of workpieces at all. Standard population in this case are such groups as groups of gears, bushes, shafts etc.;
2) by type of workpiece surface elements, for establishing of similar variants of machining for these surfaces;
3) by machining types (types of equipment, uniformity of machining attachments and community of machine set up).

Such classification gives a possibility to get:
1) strongly marked surfaces with orientation characters witch can be used for transportation and storing the workpieces in one position for using special standard equipment;
2) surfaces, witch have similar form and similar situated in the space; it gives a possibility to base workpiece in the gripper or in the special devices without additional calibration.
In terms of universality the more preferable are usage of wide-range grippers, because they give a possibility to do, in common case, the low number of gripper changing and equipment set up.

In the literature [4] the following seven main groups of workpieces for machine-building industry are given:

I – body of revolution type, length of witch (L) is low that its doubled diameter (2D), i.e. L<2D;
II – workpieces with L>2D;
III – workpieces of box-type;
IV – figuring workpieces;
V – curving workpieces;
VI – workpieces of plane type;
VII – workpieces of armature.

In this source is given the following dimensions and mass range for objects of I and II groups:

- D<160 mm; L<320 mm; m<40 kg;
- D<250 mm; L<500 mm; m<80 kg;
- D<320 mm; L<640 mm; m<160 kg;
- D<400 mm; L<800 mm; m<250 kg;
- D<620 mm; L<1250 mm; m<320 kg.

Diameter (or width) B, length L, height H and mass for objects of III group:

- B<300 mm; L<300 mm; H<300 mm; m<40 kg;
- B<500 mm; L<500 mm; H<500 mm; m<160 kg;
- B<800 mm; L<800 mm; H<800 mm; m<250 kg;
- B<1000 mm; L<1000 mm; H<1000 mm; m<500 kg.

For workpieces of others groups:

- B<300 mm; L<300 mm; H<60 mm; m<20 kg;
- B<500 mm; L<500 mm; H<100 mm; m<40 kg;
- B<800 mm; L<800 mm; H<160 mm; m<80 kg;
- B<1000 mm; L<1000 mm; H<280 mm; m<160 kg.

In terms of grasping possibility of one workpiece from a bulk all workpieces can be sorted to bunkerable (if the grasping of one workpiece from a group is possible) and not bunkerable (if the grasping of one workpiece from a group is impossible) [5].

For bunkerable workpieces are related solid, rigid, undamageble and inadherent workpieces with length up to 160 mm, width up to 30 mm and mass up to 0.16 kg. Such workpieces can be situated in the bin in bulk (without losing their characteristics), each workpiece from the bin can be grasped and orientated in space.

For the group of nonbunkerable workpieces are related:

1) big extruded workpieces, 2-D or 3-D workpieces with length more then 160 mm, width more then 30 mm, and mass up to 0.16 kg (for example: chassis, panels, plates etc.);
2) not enough hard workpieces (thin-walled cups, membranes, siphons, workpieces from wire etc);
3) fragile workpieces (for example printed circuit boards);
4) conjugateble, engageble workpieces (angles, conical hollow bodies, hooks, clamps with holes and relief parts etc).

Other classifications of the workpieces are known too.
Results

On the base of aforesaid material can make a conclusion, that the main classification characteristics of the workpieces, which can be machining on robotised workshops, are:

1) physical condition of the workpiece;
2) form and geometry of the workpiece (position and orientation of its typical axis, lines, characteristics of workpiece symmetry etc.);
3) overall dimensions;
4) range of changing errors of form and position of the workpiece parts;
5) range of the workpiece position error changing;
6) mass and other inertial characteristics of the workpiece;
7) maximal values of contact forces;
8) mobility and orientation of the workpiece in the moment of grasp etc.

In the case of requirement statements to the grasp it is necessary to indicate surfaces of grasp, direction of gripper movement before grasp, type of the gripper for this operation, value and time changing range of grasping forces, to indicate limitation to the movement, speed and acceleration of the end-effector.
1.2. Classifications of grippers

1.2.1. Grippers classification according to the GOST 26063-84

GOST 26063-84 determines the following types of the robot grippers:
1) mechanical grippers;
2) vacuum type;
3) magnetic type;
4) other grippers.

This classification is shown in Fig. 2.1.

![Diagram of gripper classification]

The common notion for the grippers of all types is conception of “working element”.

The working elements of the gripper are its parts, which directly go to the contact with object of manipulation (in this paper notions “object of manipulation” and “workpiece” are synonyms).

For magnetic grippers such working elements are elements of magnetic system, to which attracted the workpiece. For grippers of vacuum type such elements are suction cups (or suction cup) which have a contact with workpiece. For mechanical grippers such elements are jaws. The jaws can be movable or unmovable mounted on the gripper fingers.

Mechanical grippers are such grippers, which realise the grasp of the workpiece by reactions in contact points or zones of contact. These reactions are created by motors or by own weight of the workpiece.

Like one can see from Fig. 2.1 all mechanical grippers are divided into two groups:
1) grippers;
2) suspension clamps.

Gripper is a mechanism, which obtains the workpiece grasp by movement of the working elements by special mechanism, which working from the drives or springs.
Suspension clamps have not moving elements. These mechanisms obtain grasp by special bearings on which the workpiece is hold by gravitation forces.

For the group of suspension clamps are referred different buckets, hooks, pins, chutes, V-blocks etc.

Vacuum grippers obtain grasp of the workpiece by rarefied air in the closed space of a working element. This element calls suction cup. Vacuum gripper can have one or more suction cups.

There are two types of suction cups. The first one is active suction cups. In these elements the air rarefying is obtained by vacuum pomp or ejection elements. The second one is passive suction cups. The air rarefying in these elements is obtained by air displacement during suction cups deformation.

Magnetic grippers obtain grasping of the workpiece by magnetic forces, which created by permanent or electrical magnets.

1.2.2. Grippers classification according to the criterion of universality

Robot grippers can have different number of fingers, joins and degree of mobility. For each combination of these parameters correspond own gripper characteristics.

By functional possibility of the gripper can be mark out the following three groups:
1) Special grippers;
2) Multifunctional grippers;
3) Universal grippers.

1.2.2.1. Special grippers

Special grippers are used for realising concrete operation of one type. Such grippers for example are grippers with vacuum suction cups or grippers with electromagnets.

Special grippers are very effective to manipulations of big objects or very thin objects (if it is not necessary to obtain quick grippers set up for grasping another type of a workpiece). Thus application of these grippers is effective for robots in batch production; and for manipulators in batch production, large output production and in mass production.

1.2.2.2. Multifunctional grippers

Multifunctional grippers are special mechanisms for realisation a limited number of concrete grasping operations. These mechanisms have more technical flexibility than special grippers.

Grippers of this group can have greater number of fingers and joins than special grippers.

The group of multifunctional grippers can have further classifications.

For example, according to the number of fingers there are two-finger grippers, three-finger grippers, five-finger grippers etc. In production two-finger grippers are widely used. Three-finger and five-finger grippers are usually used in prosthesis.

Grippers can be classified by type of workpiece grasp: on external or on internal surfaces. External grasp for grasping on the external workpiece surfaces by fingers jamming is used. Internal grasp obtains workpiece grasping on internal surfaces by unclasping fingers.

According to the fingers movements can mark out grippers with translation jaws movement and rotation jaws movements. The grippers of first type obtain parallel positions of the jaws according each other. The grippers of second types have jaws, which rotate according to some axis.
Another variant of classification is based on a number of gripper degrees of freedom. Today in production the overwhelming majority of grippers have only one degree of freedom. The grippers with three and more degrees of freedom often not used in production.

1.2.2.3. Universal grippers
Universal grippers have usually more than three fingers and (or) more than one joint in each finger. It gives a possibility to obtain a big number of grasping operations and transferring operation of the workpiece. The big number of such mechanisms is experimental, because they have difficult kinematic, difficult control systems and big price.

1.2.3. Grippers classification according to the type of workpiece hold-in
According to the type of workpiece hold-in there are following types of the grippers [6]:
1) suspension grippers;
2) clamping grippers;
3) holding grippers.
Let’s analyse these types of grippers in details.

1.2.3.1. Suspension grippers
Suspension grippers used for grasping and holding of the workpiece in the case if a speed of the end-effector movement is small.
For this group are referred forks, loops, blades and grippers of feeder, which don’t obtain workpiece fixation (trays, V-blocks etc).
Stability of the workpiece position and orientation in such grippers by mass and form of the grasped object are mainly obtained.
Suspension grippers are often used for nonprogrammable manipulators, which used for loading and unloading operations for orientated piece blanks, and manipulation of such workpieces.
Calculation of suspension grippers consist of calculation the maximal acceleration and/or angle of lifting for the case when the workpiece displacement is equal zero. The forces between the workpiece and the gripper should be calculated too. It is necessary for calculation of maximal accelerations of the gripper in the case of parallel workpiece movement to own axis and to strength analysis of the gripper elements.
If it is necessary to realise the movement of the revolution type workpiece only in horizontal plane or along small angle to this plane the grippers with V-blocks of open type are used.

1.2.3.2. Clamping grippers
Clamping grippers are grippers of mechanical type, which obtain the workpiece grasp by friction forces and their combinations with locking forces.
These grippers have drivers, but there are constructions without drivers too.
Clamping grippers often used in robotics.
The calculation of such grippers (with drives or without ones) consist in:
1) contact force calculation in the point of contact between the workpiece and jaws;
2) strength analysis of the gripper elements and the workpiece;
3) calculation of the grasping moment, which is used for selection of drivers (for grippers with drivers) or spring (for grippers without drivers); this grasping moment should obtain a necessary value of the grasping force.

Clamping grippers especially with drivers have more difficult structure than suspension grippers, because in the clamping grippers special mechanisms for grasping force creation and control are used.

1.2.3.3. Holding grippers

Holding grippers obtain force influence to the workpiece by use different physical effects.

In production vacuum type and magnetic grippers are widely used. These are grippers, which used electrostatic voltage, adhesion, grippers with sticky contact elements etc.

Vacuum grippers obtain direct sticking to the object. This sticking is realised by discharging of the air in the bulk between the internal surface of the suction cup and the workpiece.

There are the following disadvantages of vacuum grippers:
1) noise during work;
2) low value of the workpiece fixation force;
3) troubles to obtain grasp of the workpieces with holes;
4) low life time (especially in the case of work with hot workpieces).

Vacuum grippers have the following advantages in comparison with other gripper types:
1) simple construction;
2) low gripper mass;
3) ease and high speed of clamping and unclamping the workpiece;
4) possibility to use for grasp only one side of the workpiece;
5) more homogeneous distribution of the load on the workpiece in comparison with mechanical grippers, it is avert the workpiece damage.

Vacuum grippers are very effective for transportation and assembling goods from relatively airproof materials with smooth surfaces (glass, metals, marble, granite, wood, concrete, polymers etc). For grasping and manipulations of bulky workpieces for increasing the reliability of operation the grippers with few suction cups are used. It gives a possibility to obtain good grasp in the case of missing a dense contact with some suction cups.

During grasp of slime elastic plates by big suction cups there are big deformations. These deformations can damage the workpiece material (for brittle materials) or give residual strains (for plastic materials). Application of small suction cups with diameter from 2 mm up to 8 mm which situated in the way of chess or like honeycomb excepts this risk and gives possibilities to grasp the workpieces with difficult curvilinear surfaces and through holes.

The suction cups have the greatest application in instrument-making industry, radio-electronic industry because the big numbers of workpieces in these industries (more than 50%) have curvilinear surfaces or thin plates with through holes. The masses of such workpieces are usually less than 0.2 kg.

The constructions of the vacuum grippers and their application depend on a method of discharging creation in the vacuum chamber, method of devacuumization etc. Vacuum in the suction cups can be made by suction cup deformation or by use special ejectors and vacuum pumps.
During calculation of the vacuum grippers it is necessary to get their lift capacity depending on the pressure in the vacuum caps, geometrical characteristics of these caps and external forces. These forces are gravity, technological forces, strength of wind etc. Inertial forces and strength of wind can be sum with forces which tear away the workpiece from the vacuum caps or sum with holding forces depending on the situation.

The described classification shown in Fig. 2.2.
Fig. 2.2. Classification of grippers
1.2.4. **Classification of grippers according to the type of workpiece basing**

By the type of a workpiece basing it is possible to separate the following five groups of grippers:

1) grippers with a possibility of the workpiece base changing;
2) grippers of centring type;
3) grippers of basing type;
4) grippers of fixing type;
5) grippers which not obtain basing and fixation of the object.

Grippers with transfer base possibility can change the position of the grasped workpiece by control of working elements. This property has only antroph-amorphous grippers with controlled fingers joints.

Grippers of centring type determine position of the planes, axes or centre of the grasped object. First at all it is mechanical grippers with kinematically connected fingers with jaws of V-blocks or other forms. In some situation the centring process can be realised by elastic chambers.

Grippers of basing type determine position of basing surface or surfaces. Suspension and clamping grippers are mainly belong to this class.

Grippers of fixed type keep the object position, which workpiece had in the grasping moment.

Grippers, which not obtain basing and fixation of the object, often don’t used in robotics.

1.2.5. **Classification of grippers according to the number of working positions**

Depending on the number of working positions all grippers are possible to separate to one-position type and multi-position type.

Depending on the working parameters all multi-position grippers are divided to three groups:

1) grippers of series working type;
2) grippers of parallel working type;
3) grippers of combined working type.

Grippers of series working type often are two position mechanisms, which have loading and unloading positions. Working elements of the gripper in each position work independently.

Grippers of parallel working type have several working positions for grasping or ungrasping of the workpiece group.

Grippers of combined working type have groups of parallel working positions. These groups work independently.

1.2.6. **Classification of grippers according to the control type**

Depending on the control type all grippers divided to four groups:

1) uncontrollable grippers;
2) grippers of command type;
3) fixed programmable grippers;
4) adaptive grippers.

Uncontrollable grippers are grippers with permanent magnets, vacuum cups without coercive discharging and other mechanisms for taking down the workpieces
from which it is necessary to apply bigger force value that it is necessary to holding
the workpiece.

Grippers of command type can be operated only by commands for the workpiece
grasping and ungrasping. For example there are grippers with spring drive and locking
mechanisms, which work per one tact. Clamping and unclamping of the jaws
provided by a contact of the gripper with manipulated object or parts of external
devices.

Fixed programmable grippers are operated by robot control systems. The values of
opening or closing of the jaws, the working elements relative position and grasping
force in such grippers are change depending on the program. This program can
simultaneously control the other technological equipment of robotised cell too.

Adaptive grippers are programmable mechanisms equipped by different sensors,
which give information about form of workpiece surface, its mass, grasping force,
slippage of the object relatively to the jaws etc.

1.2.7. Classification of grippers according to the type of connection to
the robot hand

Depending on the type of connection to the robot hand all grippers can be sorted
out to four groups:
1) unchangeable grippers;
2) changeable grippers;
3) quick-changeable grippers;
4) grippers for automatic changing.

Unchangeable grippers are essential parts of the robots. Changing of such
mechanisms are not provided.

Changeable grippers are free-standing robot part with basing surfaces for mounting
to the robot. These grippers provided for quick changing.

Quick-changeable grippers are changeable units with basing surfaces, which
provide quick changing of the grippers.

Grippers for automatic changing are mechanisms, which constructions provide a
possibility of automatic grippers connection to the robots.

1.2.8. Classification of gripper jaws according to the surface
characteristics

Depending on the jaws surface characteristic all grippers jaws are separated to:
1) jaws of smooth type;
2) jaws with dents (for increasing friction forces on the contact zones);
3) jaws with cover plates (for decreasing wearing of the jaws surfaces,
   improvement of the contact with workpiece and providing safety of the
   workpiece);
4) jaws with rollers (for decreasing friction forces).

Conclusions

In terms of the foregoing grippers classifications it is possible to make a conclusion
that there are huge number of different grippers and selection of one of them as an
optimal one for concrete technology operation often is not evident.
1.3 Drives of grippers

In the grippers following types of drives are used:
1) pneumatic;
2) electro-mechanic;
3) hydraulic;
4) hybrid;
5) drives with form memory effect etc.

Let’s analyse these types in detail.

1.3.1. Pneumatic drives

It is the most widely used drive type for grippers.
The main components of pneumatic drive are pneumatic cycles and motors.
The direction control of the last body (plunger or shaft of the pneumatic motor) realised by two positions valve, which operated by solenoids. For speed control of the drive the airflow valve is used.
Compressors with maximal pressure $10^6$ Pa (10 Bar) for providing the pneumatic systems by compressed air are used.
Pneumatic drives have enough low price. It is the main reason of theirs wide usage in robotics. Pneumatic drive has low stiffness; it gives a possibility to realise soft grasp without damaging the workpiece surfaces. On the other hand the low stiffness of the drive don’t gives a possibility to realise high precision object positioning.

1.3.2. Electro-mechanic drives

Electro-mechanic drives are widely used in the grippers.
There are two main types of the motors, which are used for this purpose. There are direct-current motors and step motors.
Usually in the case of electro-mechanic drive the motor is connected with reduction gear, which provide the necessary force or moment value. Today there are low-speed motors too. These motors can use without reduction gears. But these motors are very expensive for applying in production robots. Electro-mechanic drives are very easy to mount into the joints, because electrical type of operation signals gives a possibility to simplify creation an adaptive control systems based on microprocessors. Electro-mechanic drives, especially with direct-current motors, can work in force control or position control systems.

Electro-mechanic drives have the following disadvantages:
1) more expensive than pneumatic drives;
2) transient characteristic worse than have pneumatic and hydraulic drives;
3) their stiffness are low than hydraulic drives have;
4) electro-mechanic drives can’t be used in explosive space because of sparking and heat-evolution.

1.3.3. Hydraulic drives

The main components of hydraulic drives are hydraulic cylinders and/or motors.
The direction control of the end-body (of a plunger for example) is realised by two positions valve, which operated by solenoids. In such drives flow governor valves for speed control are applied. For providing system a power supply the pumps are used.
Hydraulic drives have high stiffness, can provide high force value in comparison with pneumatic drives. In contrast to the pneumatic drives they have closed loop of power supply.
1.3.4. Hybrid drives
In some cases in the grippers hybrid drives are used.

1.3.5. Drives with shape memory effect
These drives based on the applying of special materials with shape memory effect. One of such materials is based on monocrystals of Cu-Al-Ni.

Drives with shape memory effect have the following properties:
1) reversible deformations of the crystals can be made with very low speed or, if it is necessary, with very high speed too (a few microseconds);
2) property of alloys not depend from sizes and cross-sections of working body;
3) this material can provide stress up to 400 MPa, it gives a possibility to get very big force values. For example, a rod of 10 mm diameter can make a force equal 5000 kg (Fig. 3.1);
4) reversible deformations in monocrystal materials are equal 8-12 %;
5) deformation can has different character like compressive deformation, tensile deformation, flexural deformation, torsion deformation etc.

Fig. 3.1. Elements of “crystal-drive” with shape memory effect

Applying of this motor type is very effective in adaptive grippers, because such drives give a possibility to realise quick set up of the grippers without changing their construction.

There are adaptive grippers based on shape memory effect. These grippers used in robotised systems and capable to hold an object of different types (heavy metal and thin-wall workpieces of different forms) during long time. One of such gripper designed by Central R&D Institute for Robotics and Technical Cybernetics, St. Petersburg, Russia. These grippers are shown in Fig. 3.2. In these grippers the force elements with shape memory effect on the base on monocrystals of Cu-Al-Ni are used.

Fig. 3.2. Adaptive grippers

Let’s show advantages of such grippers in comparison with traditional ones:
1) there is a possibility to obtain grasping force in large range and obtain smooth speed control of the fingers by use the monocrystal allows with shape memory effect;
2) for these grippers don’t need drives of pneumatic, electro-mechanic or hydraulic type;
3) these grippers have simple constructions;
4) their mass-size characteristic in 3-5 times low than for traditional grippers, in the case of their equal power;
5) these grippers are very effective for work in extreme situations, for example in zones of high radiation, in vacuum, in aggressive environment;
6) these grippers have not wearing, noise and vibrations;
7) there is possibility to create mini- and micro-grippers.
These adaptive grippers can be used:
1) in manipulators of earth-based, air-based, underwater-based and space-based objects;
2) in the reloading equipment of nuclear reactors;
3) in technology equipment for harmful and dangerous for humans productions;
4) in technical systems and equipment for work in extreme situations.

Conclusion
In this chapter described different motors of the grippers, shown their advantages and disadvantages. Today is not possible to make a one-valued conclusion about necessity to use in the grippers construction the drives of one type, because grippers are one of the robot components, and from the terms of a possibility of control system is desirable to use in the robot the drives of one type.

The motors of different types in one robot sometimes are used too. Selection of one or other type of the motor depends on the features of robotised operation, working environment and other factors. On the base of the foregoing material the most perspective, in the opinion of the author of this paper, is usage of drives with shape memory effect, because on the base on these drives has a possibility to make light, powerful, reliable and quickly adaptive grippers and robots.
1.4. Sensors of grippers

On the grippers of production robots different type of sensors are used. It gives a possibility to increase the intelligence of the robot at all and increase the quality of realisation the technological operations.

All sensors, which are used in the grippers, depending of their price and complication can be subdivided into three groups:
1) binary sensors;
2) analogous sensors;
3) digital sensors.

Let’s analyse these sensors in details.

1.4.1. Binary sensors

Binary sensors are sensors, which give only binary signals. These signals give information about availability or deficiency of concrete event or status.

To the group of binary sensors related to:
1) microswitches;
2) optical and magnetic switches;
3) bimetal termoswitches.

Usually sensors of this type are inexpensive and simple for production and application.

Binary sensors are used like indicators of presence or absent of the workpiece, for control some parameters in certain limits (pressure, temperature etc.) or like limit switches.

Application of this type of sensors can be connected with processing of lot information too. In this case such sensors should be connected in series or parallel schemes with robot control system.

1.4.2. Analogous sensors

Analogous sensors can give analogous signals in big range. For further analysing of such signals by microprocessors they digitalisation is used.

They gives a possibility to get much more information in comparison with binary sensors.

In the grippers the following analogous sensors are used:
1) tensiometers [46, 47];
2) thermoelements;
3) piezoelectric transducers etc.

These sensors are more expensive than binary sensors. Analogous sensors in cooperation with measuring instruments and analogue-digital converters are usually used. Usually they used for receiving quantitative characteristics.

For groups of sensors and sensors which need additional signal processing are related group of tactile sensors, which situated on the gripper fingers and palms, group of visual sensors and piezoelectric sensors with active activation. Sensors of this type usually one can see only in research laboratories. But today on the market there are sensors from current-conducting rubber, which change own resistance according to the loading pressure.
1.4.3. Digital sensors

Digital sensors give information in digital form. Today the number of such sensors is increasing by production analogue sensors connected with analogue-digital converters. It gives the possibility to get signals in digital form directly from sensor units and processing of these signals by microprocessors.

All sensors, which situated in the gripper, on the robot bodies and in the working environment, if these sensors are connected with one control system, make one information system of this robot.

Classification of the robot information systems [7] is shown in Fig. 4.1.
Fig. 4.1. Classification of robot information system
Chapter 2. Standard schemes of two finger grippers. Decreasing of inertial characteristic of grippers and economy of energy

Big number of the grippers schemes is described in literature [3]. Some of them are shown in Fig. 5.1 and Fig. 5.2.

Fig. 5.1. Kinematic schemes of grippers
The simplest schemes of grippers have only one linear movable working element, which is rigidly connected with the cylinder rod. This element moves along the axis of the cylinder (Fig. 5.1 position 1 and position 2). As can see from Fig. 5.1 position 1 the gripper must be moved to the object by movement down along axis Z. In the scheme Fig. 5.1 position 2 the workpiece is entered to the gripper by its movement along axis Y. These grippers have small overall dimensions. To the disadvantages of the scheme Fig. 5.1 position 1 is possible to refer high stress loading of the rod in transverse direction.

In the scheme Fig. 5.1 position 3 the linear motions of the rod are converted to the rotation motion of one finger by use joint-hook mechanism. The disadvantage of this scheme is its big overall dimensions in contrast with previous one in the case if other characteristics are equal. It is necessary to note that one of the fingers of this gripper (Fig. 5.1 position 3) is fixed.

In construction Fig. 5.1 position 4 a scheme with rotating cylinder is applied. Such location allows to reduce the length of the plunger motion. Application of swinging cylinder limits the possibility of changing the parameters of the gripper and reduces the reliability of the mechanism (in particular by flexible pipelines application).

In Fig. 5.1 position 5, 6, 7, 8 wide-spread schemes of the tongs grippers are shown. In these grippers the fingers have mirror movement about axis X. This axis complies with axis of the cylinder. In constructions of these grippers one piston-rod cylinders are used. These cylinders have such set up that in the case of workpiece grasp the pressure go to the left part of the cylinder, which has not a rod. Increasing the range of the gripper opening is connected with increasing the length of the fingers.

The general defect of tongs grippers are fingers rotation, because in the case of rigid fixation the jaws on these fingers can not obtain the grasp of flat type workpieces, which have different thickness. So, this type of gripper usually is not used in such constructions for grasping of flat type workpieces.

On the scheme Fig. 5.1 positions 9 and 10, the last gripper bodies have a translation motion without rotation. So, the jaws, which was parallel installed on the fingers before operation, will stay parallel each other during grasp. It gives a possibility to obtain the workpieces grasp along the parallel surfaces. Such motion of the jaws is obtained by use parallelogram mechanisms.

A schemes of grippers with parallelogram mechanisms are widely used in industry. The mechanism Fig. 5.1 position 11 is similar to the mechanism Fig. 5.1 position 10. But in general for mechanism Fig. 5.1 position 11 a≠b≠c that is why the movements of its jaws are not linear. It is necessary to note that these motions are similar to linear one for some range of the gripper opening in the case if a-cosβ=c-cosα, because in the case if α and β are small the condition b²=ac is satisfied. This is condition of linear movement of the jaws.

Motions, similar to translation type, can be received by use four joint mechanisms, which are different from the parallelogram mechanisms. The mechanism shown in Fig. 5.1 position 12 is similar to the mechanism Fig. 5.1 position 9, but has shortcut external levers of the four-joint mechanisms. So, for shown positions, in which the levers are parallel each other displacements of the jaws in a short range of opening are nearly to translation. But in this scheme are not linear. Outside of this range the fingers have rotation movements.

The gripper shown in Fig. 5.1 position 13 can have a very big value of opening by selection of corresponding constructive parameter. In this case the fingers move like fingers of tongs type gripper.
It is necessary to note that all of considered above grippers have only rotation joints, therefore all of them can be simple produced and adapted for concrete requirements of technological process. It is connected with small influence of fabrication errors to the grasping error, because during grasp the clearances are compensated in one side. In the case of correct selection of mechanism characteristics the process of jam is impossible.

In a scheme shown in Fig. 5.1 position 14 there is joint which admit linear and rotation movements of the output body. Parallel fingers motion with installed jaws is provided by parallelogram mechanisms. The working elements in this case have linear movements along axis Z. This scheme is intended for object grasp on internal surfaces.

In Fig. 5.1 position 15 a scheme of the gripper with anti-parallel mechanisms is shown. This scheme of the gripper is seldom used in industry.

A gripper with kinematic scheme shown in Fig. 5.1 position 16 is widely used. In this scheme there are two slide-blocks, which move on one guide (or on two parallel guides). This scheme is enough simple, but in the case of hard requirements to the overall dimensions of the gripper can appear some problems with joints producing.

The grippers shown in Fig. 5.1 positions 17 and 18 are similar to the grippers shown in Fig. 5.1 position 5, but this two grippers have joints, which not situated on the one line and have not linear links. Such constructions allow changing the force characteristics of the grippers and the limits of opening ranges in the case of equal lengths of the links.

As it can be seen from Fig. 5.1 grippers with symmetrical fingers are usually used. Those grippers have symmetrical fingers motions about own middle plane. The schemes with asymmetrical fingers motions are used seldom. It is necessary to note that often schemes of the grippers with unmoveable drivers are used.
In Fig. 5.2 position 1 a scheme of tongs type gripper is shown. This gripper is widely used in industry. High reliability of grasp for such gripper is provided only in the case of precision production of all joints of this mechanism.

In Fig. 5.2 position 2, 3 and 4 different variants of tongs type grippers with link gears are shown. By selection of corresponding type of the link gears it is possible to get the required dependency of the grasping force from the value of the gripper opening.

In the scheme Fig. 5.2 position 2 the links have translation movement. In the scheme Fig. 5.2 position 5 cam (wedge-operated) mechanism is used. Depending on the selected profile of those mechanisms depend a type of grasping force function.
from the value of the gripper opening and a direction of the working element motion in the case of equal direction of the working stroke of the cylinder rod.

In Fig. 5.2 position 6 a scheme of the gripper with leaf springs is shown. Big number of schemes with springy elements is described in literature, but they are widely used only for grasping of the workpieces of small mass.

In the schemes Fig. 5.2 from position 6 to position 18 schemes of the grippers with gear transmission are shown.

In Fig. 5.2 position 7 scheme of tongs type gripper with rack gearing is shown. The most important difference of this scheme from the scheme Fig. 5.1 position 7 is that in the case of using rack gearing transmission can be received arbitrarily big value of the gripper opening.

In Fig. 5.2 position 8 a scheme of tongs type gripper with rack gearing transmission and parallelogram mechanisms is shown. Such construction obtains translation motion of the fingers with rigid fixated jaws.

Reliable grasp of round profile workpieces with big fluctuation of the diameter value can be obtained by using the asymmetrical mechanism of the gripper (Fig. 5.2 position 9). For obtaining a small changing of the centre mass position of the gripper in the case of grasp workpieces with different diameters, the rotation angles of the fingers must be different. So, the gears of the gripper must have different numbers of cogs.

The rack gearing transmission is widely used in the grippers, when applied motors with rotation output links (the electric motors, pneumatic and hydraulic motors). Such scheme is shown in Fig. 5.2 position 10.

For increase the grasping force in the case of using motors with rotation output links usually reduction gears are used. Such schemes are shown in Fig. 5.2 positions 11, 12 and 13.

In the schemes with gears usually have a possibility of it changing. It gives a possibility to change a reduction ratio and by this way to change the grasping force and the speed of grasp.

In the scheme of tongs type gripper which is shown in Fig. 5.2 position 13 the worm-gear is used. The main advantages of a worm-gear are a big reduction rate and possibility of applying the transmissions with self-braking. It gives a possibility to grasp the workpiece in the case of taking down the moment from the drive, it can be used for obtain a grasping process during long time.

In the scheme Fig. 5.2 position 14 a gripper with screw-gear is shown. For obtaining symmetrical motion of the slide-blocks the screw-gear transmission is used. This screw-gear has right-handed and left-handed threads. This gripper is very effective for grasping workpieces of big sizes (for example long shafts of different lengths). It is important to note that screw-gears of grippers can have the possibility of self-braking. In this case the grippers have similar characteristics like the gripper with worm-gear self-braking transmission. It is important to note that operation speed of the gripper with screw-gear and worm gear transmissions is usually not high, it limit their application.

For obtaining grasp of cylindrical and prismatic workpieces a grippers with three and more fingers can be used. One of such schemes of the gripper is shown in Fig. 5.2 position 15.

The prototype for the gripper shown in Fig. 5.2 position 16 is the kinematic scheme Fig. 5.1 position 6. But the gripper shown in Fig. 5.2 position 16 has additional joints in point A, B, C. With help of these joints the mechanism has three additional degree of freedom. It gives a possibility to obtain reliable fixation of the workpieces with
square type cross-section or cross-sections, which are similar to the square type, in the case of big displacement of the workpiece from the ideal position.

Grippers with additional degrees of the freedom during grasp usually not provide the object basing, which independent from starting position error between the workpiece and gripper. For exclude of undesirable joints displacements and fixation their positions in free statement springy elements are used. These elements are build into the joints.

In Fig. 5.2 position 17 a kinematic scheme of the gripper with one additional degree of freedom is shown. The parallelogram mechanisms in this construction provide a translation motion of the gripper jaws. The joint on the pneumocylinder rod allows to the gripper fingers move up and down simultaneously while the workpiece don’t grasp.

In Fig. 5.2 position 18 a scheme of the gripper with one additional degree of freedom is shown. This gripper has a bevel gear, which rotate the feed screw. A translation linear motion of the gripper fingers with rigidly fixed jaws is obtained by slide-blocks. The bevel gear allows to fix the workpiece in any position within a range of the slide-block movement. The object fixation is obtained by use a self-braking screw-gear.

As one can see from Fig. 5.1 and Fig. 5.2 inserting the additional degrees of freedom in the grasping mechanisms gives a possibility to increase the adaptation of the grippers to the workpiece form. From these figures one can see that there are two main tendencies:
1) the workpiece is reducing to the position, given by gripper jaws;
2) the jaws are reducing to the workpiece position.

The difficulty of realisation the last tendency is consist in necessity of a free movement of the jaws during grasping process, but the object should be rigidly fixed in the grasped position. The basing in this case is not rigid and variable.

There are schemes of grippers, which provide the grasping process of workpieces different sizes and forms.

As it is shown above there is great number of kinematic schemes of grippers, each of them has own advantages and disadvantages.

For checking correctness of the gripper choice and checking the grasp optimality is necessary to analyse a series of characteristics.

One of such characteristics, in the opinion of the author of this paper, is a function of the grasping force from the gripper opening value.

Let’s analyse some grippers.
For the gripper shown in Fig. 5.3 are equitable the following dependencies:

\[ F' = \bar{F}' + \bar{F}' \]

\[ F' = \frac{Q}{2} \frac{l_1 \cos \psi}{l_2} \]

\[ h' = a + \frac{l_2 \sin \psi}{l_2} \]

where: \( Q \) – force, created by rod of pneumocylinder or hydrocylinder;
\( h' \) - value of the gripper opening by motion only one finger;
\( F'_j \) – force, created by corresponding finger of the gripper;
F – force which go to the workpiece clamp;
F_t – force which go to the compensation of friction.

Fig. 5.3. Layout of the gripper and corresponding to this scheme the graphic of function the grasping force from the gripper opening value

On this figure also shown the mathematical model of the gripper and the graphic of function of the grasping force from the opening gripper value. The diagram on the interval [h1', h2'] is corresponding to the case if ψ<0; and the diagram on the interval [h2', h3'] is corresponding to the case if ψ>0.

For shown in Fig. 5.4 gripper are equitable the following dependencies:

\[ F' = \frac{Qa}{2l_2 \sin \alpha}; \]

\[ h' = a + l_3 \sin(\psi - \alpha) + l_3. \]

Fig. 5.4. Layout of the gripper with parallelogram mechanisms and corresponding to this scheme graphic of function the grasping force from the gripper opening value

For shown in Fig. 5.5 gripper are equitable the following dependencies:

\[ F' = Q \tan(\alpha / 2); \]

\[ h' = l_1 \sin \alpha . \]
Fig. 5.5. Layout of the gripper and corresponding to this scheme graphic of function the grasping force from the gripper opening value

For the gripper shown in Fig. 5.6 is equitable:

\[ F' = \text{const.} \]

Fig. 5.6. Layout of the gripper and corresponding to this scheme graphic of function the grasping force from the gripper opening value

Analysed above schemes of the mechanical grippers are typical in terms of the function of the grasping force from the gripper opening value. These functions are shown in Fig. 5.7.

Fig. 5.7. Functions of the grasping force from the gripper opening values

where: \( h_1, h_3 \) - minimal and maximal values of the gripper opening

From analysing Fig. 5.7 it is possible to make a conclusion that created by the gripper grasping force depends from the kinematic scheme of the gripper, selected interval of the gripper opening (\( h' \)) and values of this interval. For one type of gripper
the value of the gripper opening can be changed by selection of corresponding geometric sizes of the gripper parts. In the case of changing the value of the gripper opening if the force value created by the gripper driver is stay equal the gripper force can increase, decrease or not change.

This characteristic can be used for economy of energy by optimal gripper selection. So, it is possible to select such gripper, which in the case of smaller value of the input force (Q) creates the equal value of the grasping force (F').

Thus, in the case of reduction of necessary drive powerful is possible to use the drives of low mass, it is increase of actual carrying capacity, i.e. increase the maximal workpiece mass, which can be manipulated by this gripper and decrease the inertial characteristics of the gripper.

It is necessary to note that in the case of equal workpiece mass if the gripper has low mass the load on the robot drives is low and, so, low energy consumption in comparison with a case if the gripper has big mass.

Thus, we received a principle of optimisation by complex criterion for mechanical grippers:

For any workpiece types it is possible to select such gripper, which under smaller value of the input force Q creates the required value of the grasping force.

This principle is one of the main principles of grippers optimisation and depends on several parameters, among others:
1) mass and sizes of the workpiece;
2) possible surfaces of the workpiece grasp;
3) stability of the workpiece in the gripper;
4) coefficient of force transmission from the gripper motor to jaws of different grippers etc.

Given optimisation will be shown hereinafter.

Conclusions

In given chapter is considered row of two-finger gripper schemes and described their advantages and disadvantages. Main dependencies of the grasping force from the value of the gripper opening under single input force are shown. On the base of the foregoing material was formulated by the author of this paper the principle of optimisation of a gripper selection by complex criterion [8].
Chapter 3. Conditions of realisation technological operations

The process of workpiece manipulation is one of the parts of technological operation.

This process can be divided into the following parts:
1) grasp of mobile or immobile workpiece;
2) transportation of this workpiece to a new position with changing of its relative position in the robot gripper (for example, with the help of multi-fingers grippers) or without this changing;
3) workpiece set-up to the certain position (for example, in the case of assembly operation) or manipulation of the workpiece, in the case of robotised machining operation (for example, grinding operation with help of robot).

The process of interaction of all grippers with a manipulated object and equipment has one important feature consisting in necessity of compensation their relative position.

In the case of an ideal relative position of the workpiece 2 and gripper 1 during grasp the workpiece feels only clamping forces (Fig. 6.1 positions I). But in real because of workpiece position error, errors of its manufacturing, robot control errors and other factors take place position errors of the manipulated object relatively to the gripper jaws (Fig. 6.1 positions II). As result of this error can be arising dangerous loads in the kinematic chain Equipment - Manipulated object - Industrial robot.

These loads can be eliminated by:
1) compliance of each elements of this kinematic chain or by insertion to this chain the additional elements of compliance;
2) small movement of the workpiece in the gripper or equipment,
3) combination of these ways (for example in assembly operation).

It is necessary to note that compliance of each element of this kinematic chain on all directions in Cartesian coordinate system generally is not equal.

The total positional error of the workpiece relative to the gripper and the gripper with grasped workpiece relative to equipment, in which fixed the conjugated workpiece, generally is not identical on all directions of three-dimensional coordinate system.

On the base of the foregoing material, in opinion of the author of this paper, is possible to make a conclusion: that probability of occurrence of dangerous loads in the kinematic chain Equipment - Manipulated Object - Gripper or Equipment - Conjugated Workpiece- Manipulated Object - Gripper (in the case of robotised assembly) can be reduced by optimal selection of compliance parameters of these
Let's analyse the process of workpiece manipulation on the example of assembly operation, because during realisation of this operation there are all stages of manipulation.

Let's analyse the process of assembly of two workpieces on cylindrical surface. During connection of these workpieces it is possible to mark out four phases (Fig. 6.2):

1) approach (Fig. 6.2 positions 1);
2) chamfer crossing (Fig. 6.2 positions 2);
3) one-point contact (Fig. 6.2 positions 3);
4) two-point contact (Fig. 6.2 positions 4).

Fig. 6.2. Four stages of assembly

All of above shown assembly stages or some of them are present in each robotised operation. Therefore let’s analyse them in detail on the example of assembly operation in the case of application a remote centre compliance (RCC) and without these units.

3.1. Conditions of realisation technological operations in the case of application of remote centre compliance

The workpiece approach is a robot working motion, which transfer the workpiece to the position immediately previous to assembly operation.

The chamfer crossing is a geometrical position of assembling workpieces, at which arise a contact between one of the workpieces with the chamber of other workpiece or between the chambers of both assembling workpieces.

The assembly process in the case of applying the special device of passive compliance with remote centre on the last robot wrist is described in literature [10, 9].

Geometry of the contact and the forces, appeared during this contact, are shown in Fig. 6.3.
where: $\theta$ - angular error of an axis of the rod and an axis of the hole;
$\varepsilon_0$ - linear error of an axis of the rod and an axis of the hole;
$f_N$ – force, appeared during assembly of two workpieces (if $Q\neq 0$ and $\varepsilon_0\neq 0$);
f$_1$ and f$_2$ - components of the force $f_N$;
$\mu$ – coefficient of friction;
$F_f$ - friction force;
$Z_2$ - vector of movement the workpiece during assembly.

The geometry of the chamfer is described by its corner $\alpha$ and width w (Fig. 6.2).
It is necessary to note, that if the chamfer have both of assembling workpieces,
w=w$_1$+w$_2$; where w$_1$ and w$_2$ – width of the appropriate chamfers.

Linear and angular errors of initial position of the rod concerning to the axis of the hole arise by:
1) manufacturing errors of the end-effector;
2) inaccuracies of installation it on the manipulator;
3) deformations or wear of the gripper;
4) errors of manufacture of assembling workpieces or their deformation;
5) errors of installation of the assembling workpieces in the gripper and equipment;
6) manufacturing errors of the equipment;
7) control robot errors etc.

Thus, by reduction of the aforesaid error values it is possible to decrease the positioning error of the rod relative to the axis of the hole, i.e. to improve the conditions of the unit assembling.

One-point contact is one of assembly stages at which the assembling workpieces have a contact with each other only in one point. The forces operating at one-point contact, are shown in Fig. 6.4.
Fig. 6.4. Forces acting during one-point contact

where: A - point of contact;
Z₂ - vector of the driving direction of the workpiece during assembly;
N - reaction at support;
μ – coefficient of friction;
F\textsubscript{TP} - friction force.

Two-point contact is stage of assembly, at which the assembling workpieces adjoin in two points. The forces acting during two-point contact are shown in Fig. 6.5.

Fig. 6.5. Forces acting during two-point contact

where: A, B - points of contact;
Z₂ - Z₂ - vector of the driving direction of the workpiece during assembly;
N₁, N₂ - reaction at support;
μ₁, μ₂ – coefficients of friction;
F\textsubscript{TP\textsubscript{1}}, F\textsubscript{TP\textsubscript{2}} - friction forces.

In literature [9, 10] are mark out, that the grate part of assembling problems arises during two-point contact. The improvement of the workpiece assembling is connected with increasing of distance between points of two-point contact or prevention of such contact. The most effective way for obtaining it is reduction of distance from the end of the workpiece to remote centre compliance, i.e. some point in space, concerning of which the workpiece has only deviation by forces F_x, F_z and moment M (Fig. 6.6.). The special devices of remote centre compliance (RCC) can be one of the robot components or component part of other equipment of robotised cell.
where: $K_X$ - stiffness of linear motion;
$K_\theta$ - stiffness of angular motion;
$L_g$ - distance from the remote centre compliance up to workpiece end;
$r$ - radius of the workpiece.

In literature [9, 10] is marked out, that for definition of the opportunity of successful realisation of assembly process it is necessary to analyse not only geometrical parameters of assembling objects, but also forces operating to these objects. Thus is marked out two phenomenon’s, arising during assembly at the moment of jamming the rod in the hole in the case of two-point contact. These phenomenon’s are: jamming and wedging.

The wedging is a condition, in which the rod can’t move because affected to it through the gripper forces and moments are in incorrect ratio.

The jamming is a situation, in which the rod can’t move because of irregular geometrical ratios of the connected objects.

Sometimes the jamming leads to impossibility of completion the assembly operation and damaging of connected workpieces at any changes of the of applied force values.

The mathematical model of jamming is based on the hypothesis, that one of the assembling workpieces is not absolutely rigid, but its rigidity is higher than rigidity of the robot.

Forces arising in the contact points during jamming can act towards each other (Fig. 6.7.).
where \( f_1, f_2 \) - contact forces; 
\( \Phi' \) – angle of friction cone.

In this figure the situation when the left and right cones of the friction cone are intersected is shown. It is possible if \( l_2 \) is small. In Fig. 6.7 the limit situation is shown in this case \( l_2 \) has the maximal value at which the jamming is still possible.

The contact force \( f_2 \) (acting on the right side) does not coincide on the direction with generatrix of the friction cone. It means that on the right side the relative workpiece movement was already completed.

The contact force \( f_1 \) (acting on the left side) is directed along the lower directrix of the cone. It means, that at the left side the rod tries to ”slip out” from the hole.

In literature [9] the following conditions of successful assembly completion are given:

1) Condition of chamfer contact:

\[
/\varepsilon_0/ < w,
\]

where: \( \varepsilon_0 \) - linear error of the rod axis from the axis of the hole;
\( w \) - width of the chamfer; if both of connected workpieces have a chamfer on the corresponding assembling surfaces, than \( w = w_1 + w_2 \); where \( w_1 \) and \( w_2 \) - widths of the corresponded chamfers.

2) Condition of jamming avoiding during two-point contact:

\[
\begin{align*}
\left\{ \begin{array}{l}
/Q_2/ < c/\mu, \\
 c = (R - r)/R, \\
 Q_2 = Q_0 + \frac{K_Y \varepsilon_0 (L_g - l_2 - \mu r)}{K_X L_g^2 + K_Q - K_X L_g (l_2 + \mu r)},
\end{array} \right.
\end{align*}
\]

where: \( \mu \) – coefficient of friction;
\( c \) – dimensionless factor;
\( r \) - radius of the shaft;
\( R \) - radius of the hole;
\( Q_2 \) – dimensionless factor;
Q₀ - angular deviation of the shaft axis from the axis of the hole at the moment of the chamfer contact;
K_X, K_Q – stiffness characteristics of the RCC unit;
L_g - distance from the RCC unit to the end of the workpiece;
l_2 - distance from the edge of the hole to the point B (Fig. 6.7.).

It is necessary to mark out, that two-point contact occurs on the depth l_2:

\[ l_2 = \frac{\beta - \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}, \quad (1) \]

and disappears on the depth l'_2:

\[ l'_2 = \frac{\beta + \sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}, \quad (2) \]

where:
\[ \alpha = K_X(\epsilon_0' + L_gQ_0), \]
\[ \beta = (L_g-\mu r)\alpha + K_XL_gD + K_QQ_0, \]
\[ \gamma = cD(K_XL_g^2 + K_Q + K_XL_g\mu r), \]
\[ \epsilon_0 = \epsilon_0 + cR, \]
D = 2R.

In literature [9] on the base of assumption:

K_Q >> K_XL_g^2 и K_QQ_0 >> \mu K_X \epsilon_0',

was received the following equations:

\[ l_2 \approx \frac{cD}{Q_0}, \]
\[ l'_2 \approx \frac{K_QQ_0}{K_X\epsilon_0'} - l_2. \]

These equations with good accuracy are executed in the RCC units.

If L_g and Q_0 are small then the equations 1 and 2 have not solutions, that speaks about impossibility of two-point contact.

It is necessary to mark out, that the main part of problems during assembling operation arises at the phase of two-point contact. In the case of increasing value l_2 (the depth of appearance of two-point contact) or prevention of this phenomenon increase the reliability of assembly process.

3. Condition of avoiding of wedging:

\[ \begin{cases} M + \frac{\mu(1 + \lambda)F_X}{F_Z} < \lambda, \\ \left| \frac{F_X}{F_Z} \right| < \frac{1}{\mu}, \end{cases} \]
where: \( \lambda = \frac{l}{2r\mu} \);

1 - distance from the point A to the end of the workpiece (Fig. 6.8.).

![Diagram](image)

Fig. 6.8. Condition of the workpiece wedging

It is necessary to mark out, that all of these conditions were received in the case of applying special RCC units, which was fixed on the last robot wrist before gripper, for assembling of peg in hole type on the base on assumption, that the angular deflection of the shaft axis from the axis of the hole is small.

In the case if RCC units is not installed on the robot for assembly operations the own robot compliance is possible to use too. This compliance usually much less than has remote centre compliance; in the foregoing material it not taken into account.

On the base of literature [11, 12] it is possible to make a conclusion, that generally it is impossible to define the own centre of passive compliance for any type of the robot of an arbitrary configuration, if RCC unit does not contain in the robot construction.

If before design of a robotised operation the positions of the robot and connected workpiece are strictly given and for assembly operation it is impossible to find the centre of the robot compliance, but usage of the stiffness characteristics are necessary for calculation of this operation, than it is necessary to find the robot compliance by experimental way.

For this purpose on last robot wrist (without gripper) is necessary to install a measuring probe, optical system or sensors of other type. In the experiment it is necessary to find the compliance of the system on three coordinate axes, i.e. compliance on the axis X and -X, Y and -Y, Z and -Z, QX and -QX, QY and -QY, QZ and -QZ (where \( \pm Qi \) - compliance on the axis i in clockwise and contra clockwise direction).

Thus if in the robotised cell there is a device which able to make a position monitoring in real time and correct it with good accuracy than for designing and control of this assembly operation it is necessary to use all these data.

If such monitoring and control systems are absent and the position error of the robot is symmetric concerning to the beginning of coordinate system, connected with the last robot wrist, than on each coordinate axis from two compliance indexes it is necessary to select the least one. This index will be the index of the system compliance on the given axis.

If the position error of the robot is not symmetrical concerning to the beginnings of coordinate system, connected with the last robot wrist, than the least index of compliance for each axis will be calculated index. In this case the calculated error will be the maximal from errors on the given axis.
On the base on the foregoing material it is possible to offer two ways of calculation the successful realisation of assembly operation in the case of absence RCC unit.

The first way is connected with conditional statement of the remote centre compliance to the beginning of coordinate system on the last robot wrist and calculation of assembly operation on the base of the above-stated indexes of compliance like in the case of applying RCC unit.

The second algorithm is connected with condition of avoiding two-point contact, because at this phase the main problems of assembly (wedging and jamming) are appear.

Let's analyse conditions of realisation of assembly operation without using of RCC units.

3.2. Conditions of realisation technological operations without application of remote centre compliance

Let's analyse conditions of successful realisation of assembly operation in the case of assembly without application of remote centre compliance in the construction of robot cell:

1. Condition of chamfer contact:

\[ |\varepsilon_0| < w, \]

Where: \( \varepsilon_0 \) - linear error of the rod axis from the axis of the hole;

\( w \) - width of the chamfer; if the chamfer have both of connected workpieces on the corresponding assembling surfaces, than \( w = w_1 + w_2 \); where \( w_1 \) and \( w_2 \) - width of the corresponded chamfers.

2. Conditions of non-admission of the two-point contact:

Let's analyse conditions of two-point contact in the case of peg in hole type assembly (Fig. 6.9).

![Fig. 6.9. Two-point contact in the case of peg in hole type assembly](image)

For this figure the following equation is correct:

\[ R = r \cos \theta + 0.5 \tan \theta. \]

Let's analyse the assembling process more in detail.

Let's analyse the case, when \( l_h \geq (l_1 - \tan \theta) \cos \theta \) (Fig. 6.10).
Fig. 6.10.

where: \( l_1 \) - length of the connected part of the shaft; 
\( l_h \) - depth of the hole; 
\( d \) - diameter of the shaft; 
\( D \) - diameter of the hole; 
\( \varepsilon \) - linear position error of the rod axis from the axis of the hole; 
\( \theta \) - angular position error of the rod axis from the axis of the hole; 
\( Z_1 \) and \( Z_2 \) – possible directions of assembly.

For this case is correct the following set of equations:

\[
\begin{align*}
D &= l_1 \sin \theta + d \cos \theta, \\
\varepsilon &= \frac{l_1}{2} \sin \theta.
\end{align*}
\]

Thus:

\[-l_1 \sin \theta = dc \cos \theta - D,\]

\[l_1^2 \sin^2 \theta = d^2 \cos^2 \theta - 2D \cos \theta + D^2,\]

\[l_1^2 (1 - \cos^2 \theta) = d^2 \cos^2 \theta - 2D \cos \theta + D^2,\]

\[l_1^2 - l_1^2 \cos^2 \theta - d^2 \cos^2 \theta + 2D \cos \theta - D^2 = 0,\]

\[-l_1^2 - d^2 \cos^2 \theta + 2D \cos \theta + (l_1^2 - D^2) = 0,\]

\[(l_1^2 + d^2) \cos^2 \theta - 2D \cos \theta + (D^2 - l_1^2) = 0,\]

Let \( x = \cos \theta \), then:

\[(l_1^2 + d^2)x^2 - 2D dx + (D^2 - l_1^2) = 0,\]
The unknown maximal value of the angular position error of the axis rod from the axis of the hole $\theta$ is possible to find from the set of equations:

$$x_{1,2} = \frac{2Dd \pm \sqrt{(l_i^2 + d^2)^2 + 8Dd(D^2 - l_i^2)}}{2(l_i^2 + d^2)},$$

$\theta_1 = \arccos(x_1)$,

$\theta_2 = \arccos(x_2)$.

In this case should be satisfied the condition:

$$lh \geq (l_1 - dtg[\theta]) \cos[\theta].$$

If this condition is not satisfied, then calculation of the maximal possible values of $\theta$ and $\varepsilon$ is necessary to do by a method, which will be given below.

If the above-stated condition is satisfied, than the maximal value is possible to find by the formula:

$$\varepsilon = \frac{l_i}{2} \sin[\theta].$$

Thus, for this case the condition of non-admission of the two-point contact is formulated as:

$$\theta \leq [\theta],$$

$$\varepsilon \leq [\varepsilon].$$

Let's analyse the two-point contact in the case of the multidiameter shaft. For multidiameter shaft there are two variants (Fig. 6.11).
Thus, in the case of multi-diameter shaft with two external diameters it is necessary to analyse both possible variants. It is obvious, that the case 1 Fig. 6.11 is similar to the case shown in a Fig. 6.10.

For the case 2 Fig. 6.11 the geometrical limitations of the shaft position concerning to the axis of the hole at assembly operation are necessary to calculate by the set of equations:

\[
\begin{align*}
D &= (l_1 + l)\sin \theta + \left(\frac{d}{2} + \frac{d_l}{2}\right)\cos \theta, \\
\varepsilon &= \frac{l_l + l}{2} \sin \theta.
\end{align*}
\]

Let \( x = \cos \theta \), then:

\[
x_{3,4} = \frac{D(d + d_l) \pm \sqrt{((l_1 + l)^2 + (d + d_l)^2 / 4)^2 + 4D(d + d_l)(D^2 - (l_1 + l)^2)}}{2((l_1 + l)^2 + (d + d_l)^2 / 4)},
\]

\( \theta_3 = \arccos(x_3), \)

\( \theta_4 = \arccos(x_4), \)

It is necessary also to find values \( \theta_1 \) and \( \theta_2 \) on the base on above-stated procedure at \( d = d_1 \).

The unknown maximal value of the angular position error of the rod axis from the axis of the hole [\( \theta \)] is possible to find from the set of equations:

\[
[\theta] = \min[\theta_1, \theta_2, \theta_3, \theta_4],
\]

\([\theta] \geq 0.\)
In this case should be satisfied the condition:

\[ l_h \geq (l_1 - d_1 \tan[\theta]) \cos[\theta], \text{ if } [\theta] = \theta_1 \text{ or } [\theta] = \theta_2; \text{ in this case } i = 1, \]

\[ l_h \geq (l + l_1 - d \tan[\theta]) \cos[\theta], \text{ if } [\theta] = \theta_3 \text{ or } [\theta] = \theta_4; \text{ in this case } i = 2. \]

If this condition is not executed, than calculation of the maximal permissible values of \( \theta \) and \( \varepsilon \) is necessary to do by procedure, which will be given hereinafter.

If the aforesaid condition is executed, then the maximal permissible value \( \varepsilon \) is possible to calculate by the following equations:

\[ [\varepsilon] = \frac{l}{2} \sin[\theta], \quad \text{if } i = 1, \]

\[ [\varepsilon] = \frac{l + l_1}{2} \sin[\theta], \quad \text{if } i = 2. \]

Let's formulate a condition of non-admission of two-point contact:

\[ \theta \leq [\theta], \]

\[ \varepsilon \leq [\varepsilon]. \]

In the case if the of multi-diameter shaft, it is necessary to make calculation of the parameters \( \theta \) and \( \varepsilon \) by the similar algorithm.

It is obvious, that the above described assembly cases correspond to the case of assembly at workpiece movement on the axis \( Z_1 \) or \( Z_2 \).

Let's analyse cases, for which not executed the following conditions:

\[ l_h \geq (l_1 - d_1 \tan[\theta]) \cos[\theta] \text{ - for the simple shaft} \]

or

\[ l_h \geq (l_1 - d_1 \tan[\theta]) \cos[\theta], \text{ if } [\theta] = \theta_1 \text{ or } [\theta] = \theta_2; \text{ in this case } i = 1, \]

\[ l_h \geq (l + l_1 - d \tan[\theta]) \cos[\theta], \text{ if } [\theta] = \theta_3 \text{ or } [\theta] = \theta_4; \text{ in this case } i = 2, \]

for the multidiameter shaft.

Let's analyse the case shown in Fig. 6.12.
For this case true the following set of equations:

\[
\begin{align*}
D &= l_t \tan \theta + d / \cos \theta, \\
\varepsilon &= \frac{D}{2} - \frac{d}{2} \cos \theta.
\end{align*}
\]

Thus, after transformations:

\[(D^2 + l_h^2) \sin^2 \theta + 2d \sin \theta + (d^2 - D^2) = 0,\]

Let \( x = \sin \theta \), then:

\[(D^2 + l_h^2) x^2 + 2d x + (d^2 - D^2) = 0,\]

\[x_{1,2} = \frac{d l_h \pm \sqrt{d^2 l_h^2 - (D^2 + l_h^2)(d^2 - D^2)}}{D^2 + l_h^2},\]

\[\theta_1 = \arcsin(x_1),\]

\[\theta_2 = \arcsin(x_2),\]

The unknown maximal value of position error of the rod axis from the axis of the hole \( \theta \) is possible to calculate by the set of equations:

\[
\begin{align*}
[\theta] = \min \left[ \theta_1, \theta_2 \right], \\
[\theta] &\geq 0.
\end{align*}
\]

At that the maximal permissible value \( \varepsilon \) is equal:

\[\varepsilon = \frac{\tan[\theta]}{2} (l_h + d \sin[\theta]).\]

Thus, for this case the condition of non-admission of two-point contact is formulated as:
Let's analyse the multidiameter shaft.
There are two possible variants (Fig. 6.13).

Thus, in the case of multidiameter shaft shown in Fig. 6.13 it is necessary to analyse both of possible variants. It is obvious, that the case 1 Fig. 6.13 is similar to the case shown in Fig. 6.12.

For the case 2 Fig. 6.13 the geometrical limitations of the shaft position concerning to the axis of the hole at assembling operation is necessary to calculate by the following set of equations:

\[
\begin{align*}
D &= l_h \tan \theta + \frac{d_1 + d}{2 \cos \theta}, \\
\varepsilon &= \frac{\tan \theta}{2} \left( l_h + \frac{(d_1 + d) \sin \theta}{2} \right)
\end{align*}
\]

Let \(x = \sin \theta\), then:

\[
x_{1,2} = -2(d_1 + d)l_h \pm \sqrt{(d_1 + d)^2 l_h^2 - (D^2 + l_h^2)((d_1 + d)^2 - D^2)}
\]

\[
\theta_3 = \arcsin(x_3),
\]

\[
\theta_4 = \arcsin(x_4),
\]
It is necessary also to find values $\theta_1$ and $\theta_2$ by the foregoing procedure at $d=d_1$.
The unknown maximal value of position error of the rod axis from the axis of the hole $[\theta]$ is possible to calculate by equations set:

$$\begin{cases} [\theta] = \min[\theta_1, \theta_2, \theta_3, \theta_4], \\
[\theta] \geq 0. \end{cases}$$

If $[\theta] = \theta_1$ or $[\theta] = \theta_2$, then $i=1$;
if $[\theta] = \theta_3$ or $[\theta] = \theta_4$, then $i=2$.

The maximal permissible value $[\varepsilon]$ is possible to find by the following equations:

$$[\varepsilon] = \frac{\operatorname{tg}[\theta]}{2} (l_h + d \sin[\theta]), \quad \text{if } i=1,$$

$$[\varepsilon] = \frac{\operatorname{tg}[\theta]}{2} \left( l_h + \frac{(d + d_i) \sin[\theta]}{2} \right), \quad \text{if } i=2.$$

Let's formulate the condition of non-admission of two-point contact:

$\theta \leq [\theta]$, 
$\varepsilon \leq [\varepsilon]$.

In the case if the shaft has more steps, it is necessary to make a calculation of $\theta$ end $\varepsilon$ on the similar procedures.
The above described two cases of assembly are correspond to assembly at the case of workpiece motion only on the axis $Z_1$.
Thus, it is possible to make a conclusion that the possible directions of assembly depend not only on the position of the clamped in the equipment workpiece and robot possibilities, but also from the shape and sizes of the assembling workpieces.
It is possible to offer assembly algorithms in the case if $\theta>[\theta]$. One of such algorithms is shown in Fig. 6.14.
For this algorithm the main factor, which shows the necessity to rotate the workpiece on some angle (step), is attaining of the contact force in the point $A_i$ ($i=1,2,3, \ldots n$; $n$ - number of steps) some value, which is less than some limited force at which lose the quality of the assembling unit. In this case for assembly force monitoring it is necessary to use force-torque sensor fixed between the last robot wrist and the gripper, on the robot, on the assembling table or on the equipment. The application of other type sensors for such assembling operation is possible too.

It is necessary to mark out, that the angle of the chamfer ($\alpha$) in the case of workpiece movement only on the axis $Z_1$ (Fig. 6.15) should satisfy to the condition: $\alpha \leq (90^\circ - [0])$. 

Fig. 6.14. Assembly with help of force-torque sensors.

Fig. 6.15.
It is necessary to mark out, that in the foregoing cases the robot compliance is not used. Given calculation can be applied when the robot has a big stiffness and a compliance of the workpiece is neglect small.

These calculations can be used in the case of connection of the workpiece with a hole on the shaft, which fixed in equipment.

In the case of assembly operation shown in Fig. 6.16 is impossible to assembly the unit according to the connection surfaces at \( l' > (d' - d) \tan \theta / 2 \) without usage of the robot, equipment and/or additional elements of compliance.

\[
\theta \leq \arctan(2l'/(d' - d)).
\]

Fig. 6.16.

This limitation can take place and in the case of an excessive approach of the gripper jaws to the face plane of the assembling workpiece, i.e. the surface which can be used for grasp is limited below by value \( l_c \), Fig. 6.17.
If \([\theta]>\arctg(2l'/(d'-d))\) and there are rigid fixation of both workpieces the assembly operation can be realised only with help of elements of remote centre compliance. Such case is shown in Fig. 6.18.

![Fig. 6.18.](image)

At this: \([\varepsilon]\leq(D-d)/2\).

Such assembly is possible only by use remote centre compliance, which is installed before the gripper, the axis of this RCC unit should coincide with the workpiece axis; and/or on the shaft clamping device, so that its axis coincided with the axis of the shaft.

On the base of the assumption about non-admission of two-point contact, it is obvious, that the force limitations will arise only by production inaccuracies of the connecting surfaces, their deformation by fixation, errors at installation and fixation, and robot control errors.

If there are limitations to the angle of the shaft rotation concerning to the axis of the hole it is necessary to the foregoing limitations to add another one to the angle of rotation relatively to the axis Z. The axis Z is go through the gripper and in the case of ideal assembly \((\theta_i=0, \varepsilon_i=0)\) coincides with its direction.

In the case if assembly operation is realised not on cylindrical surfaces, that it is necessary to find the maximal permissible parameters \(\theta\) and \(\varepsilon\) for each cross-section of the connecting workpiece. In this case if there is advanced robot monitoring system, that the assembly operation is necessary to realise with taken into account all received values \(\theta_i\) and \(\varepsilon_i\) \((i=1,2,3, \ldots, n)\); where \(n\) - number of not identical cross-sections). If such system is absent, that:

\[
\theta_i=\max[\theta_1, \theta_2, \theta_3, \ldots, \theta_n],
\]

\[
\varepsilon_i=\max[\varepsilon_1, \varepsilon_2, \varepsilon_3, \ldots, \varepsilon_n].
\]

There are also other ways of assembly; for example assembly by vibration, assembly with heating or/and with cooling of the workpieces etc.
It is necessary to mark out, that the value of linear position error of the rod axis from the axis of the hole ($\varepsilon$) depends on the distance from the place of mounting of the gripper up to the face plane of the grasped workpiece (Fig. 6.19).

![Fig. 6.19.](image)

Thus, decreasing of value $L$ in the case of constant value $\theta$ carries on to decreasing of the value $\varepsilon$ and so increase the quality of assembly operation. I.e.:

$$L=f(\theta, \varepsilon).$$

In this formula magnitude $\theta$ is a parameter of the robotised cell and depends on the choice of the robot and ancillary equipment. The magnitude $\varepsilon$ depends as from the choice of the robot and ancillary equipment as from the constructive sizes of assembling workpieces.

So, in generally is possible to select such part of the workpiece, that in the case of this workpiece grasp inside of this zone by this gripper type the assembly operation always will be done with required quality.

It is necessary to mark out, that in the some cases the accuracy of the robot subject to applying its compliance on some coordinates can be not enough for realisation of this assembly operation. The author of this paper suppose, that the given limitation can be eliminated in some cases by decreasing of the grasping force value on a small value immediately during assembly operation (no more than 8-10 % from the minimal required grasping force). For example, in the case of grasp the flat workpiece by a gripper with two flat jaws the additional compliance can be obtained during assembly on the axis $X$ (Fig. 6.20) in the case of decreasing grasping force.
where: 1 - gripper;  
2 - flat jaw;  
3 - flat workpiece.

It should give the effect in the case if the workpiece movement on the axis Z is impossible or limited, for example by construction of the gripper or workpiece. Such cases are shown in Fig. 6.21.

It is necessary to mark out, that in some cases realisation of the assembly operation implies presence of forces impeded for the assembly operation. For example in the
case of connection with latches or for assembling with a tightness or on the transient planting. In such cases if the assembling process is realised on several surfaces simultaneously the axis of the gripper (Z) should coincide with a line, on which situated the resultant of these forces.

In the case if it is necessary to realise rotation of one workpiece relative to another one, for example t Birthed conjunction, the axis Z should coincide with rotation axis of the clamped in the gripper workpiece.

The foregoing requirements are connected with non-admission of acting additional forces and moments during assembly and necessity of realisation complex movements by robot.

It is necessary to mark out, that surfaces which can used for grasp of the shaft type workpieces are limited not only below by magnitude $l_C$, but also above by magnitude $l_3$. The magnitude $l_3$ is equal to minimal height of the jaw ($l_3$), which is necessary for basing the object in the gripper with required accuracy (Fig. 6.22). This given value can be increased by constructive characteristic of the assembling workpieces.

![Diagram](image)

**Fig. 6.22.**

**Results**

For definition of an opportunity of realisation of assembly operation in terms of geometrical limitations, in the opinion of the author of this paper, it is necessary to define the type of connection, possible directions of assembling process, position error of the end of the workpiece ($\theta, \varepsilon$), necessity of usage RCC units. It is necessary to find the positions of the resultant vector of the system of forces obstructing to the assembling process. This vector should coincide with the axis of the gripper. Also it is necessary to define the magnitudes $l_C$ and $l_3$ for determination of possible surfaces of the workpiece grasp.

The available workpiece length ($l_{POL}$), suitable for a realisation of grasping process, is equal:

$$l_{POL} = l - l_C - l_3,$$

where: $l$ - length of the workpiece;

$l_C$ - length of the workpiece which is necessary for realisation of this technological operation;

$l_3$ - length of the workpiece which is necessary for its fixation in the gripper.
In the case of workpiece motion on the axis Z there is the following limitation:

$$l_{\text{ПОЛ}} \leq l_{G}.$$  

It is necessary to mark out, that the value $$l_{G}$$ depends on the value of the gripper opening. If the workpiece has a complex shape, the magnitude $$l_{\text{ПОЛ}}$$ can be cut in addition blocks subject to the opportunity of fixation in the gripper.

Thus, in the case of necessity of grasp the workpiece with complex shape by the foregoing procedure it is possible to find all possible surfaces of grasp, the grasp on which does not contradict to the conditions of realisation this technological operation in terms of geometrical limitation.
Chapter 4. Workpiece basing in the grippers

During workpiece seizing it is possible to select two processes, which provide setup of the manipulated object in the gripper. There are basing and fixing.

The basing process is consist in giving to the workpiece a certain position concerning to the gripper. This process can take place before realisation of the seizing process (by means of special orientating devices and equipment located on the robot, inside or outside of its working zone) or during grasp (by means of orientating devices and equipment, located on the gripper).

Let’s analyse the basing process in details.

4.1. Rule of six points for grippers

Depending on the type of technological operation it is necessary to perform full or partial orientation of the workpiece concerning to the gripper. In the first case it is necessary to give to the workpiece an accurate position in the gripper. In the second case the accurate workpiece position in some directions is not required, because a free position of the workpiece is allowed by technological operation for some coordinate axis of the gripper. For example, allowed rotation of the cylindrical workpiece around own axis in the case of installing it in the chuck of a lathe or in the robot gripper for future machining.

The position control of the workpiece during basing process is realised by different sensors, features of technological operation including application of grippers and devices with basing elements.

The invariance of position, added to the workpiece during basing process, is remained by the object fixation. This process is realised directly by gripper construction and grasping forces.

For providing the workpiece full orientation the number and position of bearings should be such, that at conditions of the regularity contact between bases and bearings (i.e. at saving a thick and still contact between these elements) the workpiece can not move or rotate relatively to the axis of coordinate system. All degrees of the workpiece freedom are losing in the case of execution this condition.

The number of the bearings (points), on which is fixed the workpiece, must not be more than six (the rule of six points) [13]. To provide stability of the workpiece position in the grasping device (including grippers) the distance between bearings is necessary to choose as long as possible. Because with increasing of this distance decrease the influence of a form error of the base surfaces (i.e. surfaces on which the workpiece basing process is realised) to the workpiece position in the device. The basing surfaces are surfaces of the workpiece and technological devices, which directly used for the basing process. It is necessary to note that during workpiece installation to the bearings the tilting moment must not arise.

The main bearings are necessary to hardly connect with the body of grasping device. In this case though the form and size errors of the workpiece base surfaces the workpieces always have a contact with bearings in six points, which are situated in the same places. That is why each workpiece of the lot has equal stability.

It is necessary to note that during grasp of not enough hard workpieces often is necessary to increase the number of bearing points. In this case the number of contact points can be more than six.
The additional bearings should be only adjustable type or selfplaced type. In the case of applying such bearings during workpiece set-up they separately move and self-install relatively to the workpiece. After this such bearings should be fixed in these positions. So, they work like fixed bearings during technological operation. The number of additional bearings is not limited, but for simplification of the grasping device construction and to increase its accuracy and reliability of work this number must be minimum.

As adjustable or selfplaced bearings in the robot grippers vacuum cameras, pneumatic and hydraulic plungers etc. can be used.

The bearings of point type are produced like installing elements with small contact surfaces. To this group are related: fixed bearings, V-blocs (for set-up cylindrical workpieces) and bearings of other forms. These bearings provide sufficient stability of the workpiece independently of their form and size errors. To the disadvantages of basing to the point bearings are related damage possibilities of the workpiece base surfaces if the grasping force is big and the workpiece move as a result of contact deformation in the contact points. In the case of small surface roughness the base surface must be increased, so small form errors have not considerable influence to the system stability. In the case of workpiece set-up to the plain bearings different bearings plates can be used. Than below accuracy and more roughness of the workpiece base surfaces that in greater degree it is necessary to localise the place of their contact with device bearings. The workpiece set-up by one base to the bearings with big contact surface and other bases to the bearings of point type is possible too.

From foregoing material follows that the rule of six points in the best way answers to installing the workpiece to the point bearings in the case of their full orientation in space.

Except workpiece set-up with full clamping of its base surfaces to the device bearings the set-up by covering and covered base surface is used too. For these set-ups the workpiece is installing on the adjusting element or is inserting in it with some guaranteed clearance. It gives a possibility to install the workpiece into a mandrel or adaptation-companion and extract it after machining.

For installation schemes by covering and covered base surfaces with full object orientation in space the rule of six points is applicable too.

For workpiece deprivation of all degrees of freedom can be used different combined ways. For example, workpiece set-up by two holes with parallel axis and a plane perpendicular them.

4.2. Ways of the object basing in the two-fingers grippers

In production practice usually it is necessary to realise installing workpieces on different surfaces, planes and points, some of which are situated in the workpiece body too (for example, on a middle plane, axis of symmetries etc.). The main ways of the object basing in the two fingers grippers depending on the basing requirements [3] are shown in Table 8.1.
In this table:
A – jaws have translation motion on the line relatively to the gripper;
B - jaws have translation motion on the circle arc relatively to the gripper;
C - jaws make rotation motion in the plane of the drawing;
α - jaws have symmetrical motion;
β - jaws have asymmetrical motion, one of they is fixed on the gripper base;
γ - jaws move with given ratio.

From Table 8.1 it is possible to make a conclusion that for precision object basing on one of the workpiece surfaces is reasonable to use grippers with one unmoveable jaw, on surfaces of which it is necessary to realise the object basing. For this purposes can use grippers with symmetrical moving jaws of trapezoidal profile. In this case one of the jaw surfaces has a common plane with other jaws and given plane coincides with workpiece basing plane. In the both cases the jaws have translation movements.

It is necessary to note that for this task the grippers with all movable fingers can be used. In this case the jaws, on which is used for the basing process, must have a position sensor for exact determination of the basing plane.

For the object basing on the middle plane or on the axis of symmetry the grippers with both movable jaws are necessary to use.
Herewith in the case of basing on the middle plane for symmetrical workpieces advisable to use the jaws of identical profile or such profiles that in the ideal case the middle plane of the workpiece coincide with the gripper axis.

For basing on the axis or centre of symmetry it is necessary to use jaws with centring elements (for example prismatic). In this case it is necessary to use surfaces of the workpiece symmetry.

Described above logic can be used for object basing in multifingers grippers too.

From Table 8.1 one can see, that the gripper with symmetrical moving on direct line jaws is the most universal, because the positions of a central plane, lines or points in this case is completely determined and does not depend on inaccuracy of the workpiece manufacturing. The least universal are grippers with rotation fingers motion.

**Conclusion**

On the base of the foregoing material, on the opinion of the author of this paper, it is possible to make a conclusion that in the case of finding the optimal gripper for concrete robotised operation one from the choice conditions will be the following criterions:

1) criterion of gripper fingers mobility during grasping process;
2) possibility of determination of fingers position during grasp;
3) type of the applied jaws.
4.3. Surfaces of the workpiece grasp and conditions of the optimal gripper jaws selection depending on the workpiece form

In general it is possible to grasp a workpiece on different surfaces, herewith even at the case of grasp on one workpiece surfaces by one gripper it is possible to use the jaws of different forms. In those cases appear different conditions of limiting a manipulation process.

4.3.1. Conditions of optimal gripper jaws selection depending on the grasping workpiece form

Let’s analyse conditions of optimal selection of the gripper jaws depending on the form of the grasping workpiece.

For selection a construction of grasping element it is necessary to analyse the optimal conditions of realisation kinematic connection Gripper – Manipulated Object, which put to the workpiece sufficient and not redundant links during capturing and manipulation.

The widely used combinations of the jaws [6] are shown in Fig. 9.1.

![Fig. 9.1. Widely used forms of the grippers jaws](image)

In this figure: 1 - flat jaws; 2 - combination of the flat and prismatic jaws; 3 - prismatic jaws; 4 - cylindrical jaws.

There are jaws with curvilinear profile too.

The gripper with rigid jaws theoretically in a plane can have a contact with the workpiece surface maximum in three points. Those points are points of putting links to the grasped object. The total number of contact points of the manipulated object with gripper jaws for full workpiece basing should not exceed six. The number of links should be sufficient for object hold-in in the required position, and place of their superposition did not become an obstacle for execution of technological operation. But in practice not-linearity of the object generatrixes, production errors and error of the workpiece form increase the number of contact points. Besides, wrong jaws selection promotes to the addition links appearances, which worsen the conditions of the object grasping and holding. Those additional links can become a source of additional deformation in the chain Gripper-Object-Device or in the chain Gripper-Object-Conjugated Detail.

So, the gripper shown in Fig. 9.1 positions 3 can be used only if one of the jaws of V-block type has a compliance concerning to the gripper finger for own position error compensation.
4.3.2. The ideal case of symmetrical workpiece basing in two-finger grippers

Let's analyse the ideal case of workpiece basing in the gripper.

For each combination of the links gripper - manipulation object is possible to define the index of the link, which is characterised by defined variant of link superposition (k - number of contact points between gripper jaws and manipulated object) and degree of freedom for this workpiece (v), see Table 9.1 [14].

The stated below in the chapter 4.3 material is made by author of this paper.
Table 9.1. Different variants of grasp

<table>
<thead>
<tr>
<th>Jaws Forms</th>
<th>Workpieces</th>
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</tr>
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<td><img src="image6" alt="Workpiece 3" /></td>
</tr>
<tr>
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<td>k=2; v=4</td>
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</tr>
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<td>v=6-k₁/₂</td>
</tr>
<tr>
<td><img src="image22" alt="Equation" /></td>
<td>v=6-2k₁/₂, if k₁/₂ max&lt;3</td>
</tr>
<tr>
<td><img src="image23" alt="Equation" /></td>
<td>v=2, if k₁/₂ max≠1</td>
</tr>
</tbody>
</table>

Equation:

\[ v = f(k) \]

v=6-k₁/₂

v=6-k₁/₂, if k₁/₂ max<3

v=2, if k₁/₂ max≠1

v=6-2k₁/₂, if k₁/₂ max<3

v=2, if k₁/₂ max≠3

v=6-k₁/₂, if k₁/₂ max<3

v=2, if k₁/₂ max≠1

v=6-k₁/₂, if k₁/₂ max<3

v=2, if k₁/₂ max≠1
In this table:
- \( k_{1/2} \) - number of contact points between jaw and workpiece;
- \( k_{1/2\text{max}} \) - number of contact points for jaw which has its maximal number;
- \( k_{1/2\text{min}} \) - number of contact points between jaw and workpiece which has its minimal number.

It is necessary to note that the number of degrees of freedom of the object (v) determines the number of possible workpiece deviations from the ideal position in the gripper. If the given location scheme of possible devaluation does not satisfy to the scheme of possible devaluation at which it is possible to realise this robotised operation, that given operation in the case of applying such grasp can be not realised with required quality.

For two-finger grippers with two jaws the number of contact point between the jaws and manipulated object is possible to calculate by formula:

\[
k = k_{1/2}^{\text{max}} + k_{1/2}^{\text{min}},
\]

or

\[
k = k_1 + k_2,
\]

where: \( k_1 \) – number of contact points between the workpiece and the first jaw; \( k_2 \) - number of contact points between the workpiece and the second jaw.

If the gripper has a greater number of jaws, the number of contact points between the workpiece and the jaws can be found by formula:

\[
k = \sum_{i=1}^{n} k_i, \quad n=1,2…,n;
\]

where: \( k_i \) – number of contact points with jaw i; 
\( n \) – gripper jaws quantity.

From this table there are exceptions. These exceptions connect with different size correlations of the workpieces and grippers jaws. These cases are shown in Table 9.2.
It is necessary to note that in general the gripper jaws can have different form.

As one can see from Table 9.1 by degree of agreement of the form of the gripper jaws with the object form it is possible to separate:

1) completely compatible working elements, their form completely coincide with the form of the grasped object (in such case their \(v=0\));
2) partly compatible working elements (\(v=1, v=2\) or \(v=3\));
3) demi-compatible working elements (\(v=4\));
4) not compatible working elements (\(v=5\)).

For example, \(v=1\) in the case of grasp the cone on cone-shaped surface by jaws which copy the form to its surface (Fig. 9.2); \(v=2\) in the case of grasp the cylinder on cylindrical surface by jaws of similar form (Fig. 9.3). In the case of the flat object grasp on the corresponding surfaces by flat jaws \(v=3\) (Fig. 9.4). Some grasping schemes with completely compatible jaws to the form of the grasped object (\(v=0\)) are shown hereinafter.
Fig. 9.2. The cone grasped by jaws with cone-shaped surface, which copy the workpiece form

Fig. 9.3. The cylinder grasped by jaws, which copy the workpiece form

Fig. 9.4. The grasp of the flat type object on the corresponding planes
On the base of tab. 9.1 one can see, that for simple form objects with one type surfaces in the case of contact with one type jaws of two fingers gripper the number of degree of freedom depends only from contact type between one of the jaw and the workpiece. It’s mean that in the ideal case the second jaw realise only fixation of the workpiece in the gripper. This jaw can be changed for another one, which can make a contact with workpiece only in one point. This contact point should stay on the line AB (Fig. 9.5.).

![Fig. 9.5. Grasp of the flat type object by cone jaws](image)

Line AB is a line of applying grasping force. On this figure this line goes through the centres of the joints, which connect fingers of the gripper with their jaws.

If the jaws are rigidly fixed on the fingers this line coincides with a resultant force of the grasping and friction forces of one jaw and perpendicular to the line of assembly.

Thus, for not deformable workpieces, the grasps shown in Fig. 9.6 and Fig. 9.7 are equivalent.
Fig. 9.6. Grasp of the flat type object on parallel surfaces by two-fingers gripper with flat jaws

Fig. 9.7. Grasp of the flat type object on parallel surfaces by two-fingers gripper with one flat and one cone-shaped jaws

If the gripper jaws axes are not parallel each other (i.e. jaws rotated around axis AB relative to each other) and in the ideal case every jaw has two points of contact with the workpiece (for example flat type workpiece and gripper with cylindrical jaws) that it is possible to change one of them to a jaw with three contact points, which are not situated on one line; and the second one – to a jaw with one contact point. Thus grasps shown in Fig. 9.8 and Fig. 9.9 are equivalent.
Fig. 9.8. Two-fingers gripper with cylindrical jaws, rotated to the 90° relative to each other

Fig. 9.9. Two-fingers gripper with one flat jaw and one cone-shaped jaw

In the case of workpiece basing by centre holes, through or blind holes or other directing surfaces of this type if they not situated on the line AB (Fig. 9.5.) or on lines which are parallel to this line, the number of the workpiece degree of freedom is equal 0 (Fig. 9.10 and Fig. 9.11). Thus schemes Fig. 9.10 and Fig. 9.11 are the schemes with completely compatible working elements.
Fig. 9.10. Grasp with completely compatible working elements in the case if the centre holes are situated on the one side of the workpiece.

Fig. 9.11. Grasp with completely compatible working elements in the case if the centre holes are situated on the opposite sides of the workpiece.

If the centre holes which used for basing process are situated only on the line AB or only on a parallel line that the number of the workpiece degree of freedom is equal 1 and this line, on which situated the centre holes, is the axis of workpiece rotation (Fig. 9.12 and Fig. 9.13).
Thus, from analysis of Table 9.1, Table 9.2 and Fig. 9.6, Fig. 9.7, Fig. 9.8, Fig. 9.9, Fig. 9.10, Fig. 9.11, Fig. 9.12 and Fig. 9.13, with taking into account the foregoing material, it is possible to make a conclusion that for any type of two-finger grippers in the case of workpiece grasp by opposite sides, which have surfaces of one type, it is possible to go to the ideal model of the grasp, in which one of the jaws has only one contact point with the workpiece and the other one - one or more contact points.

This grasping model is possible to construct in the case of applying multi-fingers gripper for grasping workpiece of arbitrary form by conventional integration of several jaws too.

All surfaces can be classified to several classes:
1) first class - cone, sphere etc. (one contact point with an object of plane-type);
2) second class - cylinder, inverse prism etc. (two contact points);
3) third class – plane etc. (three contact points).

From the foregoing material one can say, that in the case of workpiece grasp on the external surface the number of contact points for each jaw is equal to the minimum from the classes of two contacted surfaces.

If two-finger gripper has two jaws, this value is equal to the index \( k_{1/2} \), i.e. is equal to the number of contact points between the jaws of two-finger gripper and the workpiece if the two-finger gripper has or reduced to the gripper with one jaw – point-leg, i.e. forbids the workpiece movement along AB.

**4.3.3. Rules of reducing of a two-finger gripper to the gripper with one jaw - point-leg in the case of a workpiece grasp on external surfaces**

Let’s formulate the rules of reducing of a gripper with two fingers in the case of grasp on external surfaces to the gripper with one jaw - point-leg:

**Step 1.**

If one or several (both) of the gripper jaws do not provide the contact with the workpiece in the point amount, corresponding to it (their) class, that its (they) it is necessary to change to the jaw (jaws) of the lower class at the invariance positions of the contact points between the jaw (jaws) and workpiece.

**Step 2.**

1. If the workpiece surfaces, which used for grasping process, have one class and gripper jaws are identical or have one class and symmetrical located in space relatively to the gripper axis, that one of them must be changed by point-leg.

2. If the workpiece surfaces which used for grasping process have one class and the gripper jaws are identical or have one class and rotated relative to each other on the axis which complying with line AB, and under such location the contact points can not situated opposite each other relative to the gripper axis, that one of the jaws must be changed to a jaw with class by one order bigger than source one and the second jaw must be changed by the point-leg by such way that reducing model of the gripper relative to the workpiece is stay equivalent.

3. If the jaws have different classes, but they provide the contact with the workpiece in the point amount each corresponding to its class, that the jaw with smaller class can be replaced to the jaw-point-leg.

It is necessary to note that in the reducing model of the gripper the single point-leg must be situated on the line AB.

**Step 3.**

The index of the gripper \( (k_G) \) is equal to the amount of contact points between the jaw (not point-leg) of the reducing gripper i.e. to the class of this jaw.
I.e.:

\[ K_G = k_{jaw} \]

It is necessary to note that self-setting jaws at the gripper reducing to the gripper with one of the jaws point-leg are not taken into account.

For workpieces of more complex forms, the opposite sides of which have a different form (for example: flat and cylindrical surfaces, flat and ball surfaces etc.) at searching for the optimal variant of grasp by method of possible grasping surfaces selection for each of the workpiece sides is necessary to build the ideal model of the grasp and after that take into account an interference on contact points and degree of freedom of the ideal models for opposite sides of the workpieces. On the base of these data and requirement about necessary degree of freedom of the workpiece and its conjunctive surface or type of machining on given operation follows to make a conclusion about optimal grasping type for this robotised operation.

4.3.4. Rules of reduction of a multi-finger gripper to the gripper with one jaw - point-leg in the case of workpiece grasp on external or internal surface

Before than formulate the rules of reduction the multi-finger gripper in the case of a workpiece grasp on external or internal surface to the gripper with one jaw – point-leg it is necessary to enter the following theorems:

**Theorem 1.**

Every jaw of difficult form can be changed by jaws of simple forms without changing quantity and positions of the contact points; each of the new jaws is obtain only one contact point with the workpiece.

I.e. the grippers shown in Fig. 9.14 are equivalent.

![Fig. 9.14.](image-url)

**Corollary from the theorem 1.**

If the workpiece have two contact points with a jaws of arbitrary form and grasping forces in these points are not situated on the one line and not direct to the toward each other, it’s mean that these jaws can be changed by one jaw of more difficult form.

After that it is necessary to correct the grasping scheme according to this changing.
The workpiece cross-section between two points (A₁ и A₂) on the surface has convex surface area (Fig. 9.15 position 1) if in the case on horizontal position of the line, which connect these points, this investigated surface is situated beyond to the base workpiece surface, and in this case the potential energy of the mass point, which move from one point (A₁) to another one (A₂) and back on investigated surface, on the first not dead segments have increasing function.

If in the similar situation the potential energy of the mass point moving on the investigated surface on the both directions has on the first not dead segments decreasing function (Fig. 9.15 position 2), it means that in terms of grasp this surface has concave surface.

![Fig. 9.15. Convex (position 1) and concave (position 2) workpiece surfaces](image)

A₁, A₂, A₃, A₄ – contact points; 1, 2 – investigated surfaces

**Theorem 2.**

If the workpiece has contact with a jaw in two points and their surface between these points has convex or concave surface, and in these points have not points of inflection of potential energy moving mass point, such jaw is centring jaw for this workpiece in the plane, which is perpendicular to the jaws surfaces and go across the contact points. I.e. its motion along the line, which goes through these points of contact, is impossible.

The positions of centring planes (a and b) for concave and convex workpieces are shown in Fig. 9.16. These planes are perpendicular to the plane of the drawing.

![Fig. 9.16](image)
**Theorem 3.**
If the workpiece has contact with a jaw in two points and during mass point motion on the workpiece surface between these two points in a point near contact points only in one direction the potential energy is increasing function, that in the opposite given direction the linear movement of the workpiece is limited (impossible).

This theorem is shown in Fig. 9.17.

![Fig. 9.17](image)

**Corollary from the theorem 3.**
If there are two parallel planes, workpiece movement in which is limited in two opposite each other directions, such group of planes is centring in these directions.

This corollary is shown in Fig 9.18.

![Fig. 9.18](image)

**Theorem 4.**
If the workpiece has two intersecting centring planes, this workpiece is centred on two planes, one of which is coincide with one of the real centring plane and the other one is perpendicular to this plane.

This theorem is shown in Fig. 9.19.
On this figure a and b – two intersection centring planes; a and c – two intersection centring planes which are equal to original ones (a and b).

**Theorem 5.**
If the workpiece movement in two intersection planes, which are perpendicular to the gripper jaws in the points of contact, is limited, it means, that workpiece movement is limited in the plane, which go across the intersection line of these planes, containing the bisector between these planes, in the bisector direction, and the centring plane, which is perpendicular to this limited plane.

This theorem is shown in Fig. 9.20.

In this figure a and b – two original intersected planes, the workpiece movement in which in one direction are limited; c - plane, the workpiece movement in which in one directions is limited; d – plane of centring, which is perpendicular to the plane c.

**Theorem 6.**
If the workpiece section has a point-contact with the jaw, it’s mean, that the perpendicular to this section axis, around of which can be rotate the workpiece, is go only across the perpendicular to the tangent of the workpiece in this contact point.

This theorem is shown in Fig. 9.21.
In this figure A, B and C – points of contact between the workpiece and gripper jaws; a – tangent to the workpiece surface in the contact point A; b – axis on which can lay axis of workpiece rotation, which is perpendicular to the drawing plane.

**Theorem 7.**
If in the case of vertical position of perpendicular to the tangent of workpiece in the contact point the workpiece body is situated under this point, and in this case the potential energy of motion on its surface point is increasing, it’s mean that the possible axis of workpiece rotation, in the case of movement in this direction, is situated on this axis up to the contact point. If in the similar situation the potential energy of motion on its surface point is decreasing, the possible axis of workpiece rotation, in the case of movement in this direction, is situated on this axis below to the contact point.

This theorem is shown in fig 9.22. In this figure the possible axis of workpiece rotation are shown too. These axis are perpendicular to the drawing plane.

**Theorem 8.**
If in the case of analysing the possibility of workpiece rotation to this direction all tangents in parallel planes to the corresponding contact points have common normal, and the position of this normal is answered to the requirements of the theorem 7, such normal is rotation axis, around of which the grasped workpiece can be rotated in this direction.

This theorem is shown in Fig. 9.23.
List of publications of Nikolay Krys