ABSTRACT

The calculation and explanatory note contains 116 pages, 56 figures, 12 tables, 16 sources, 1 graphic application .

mobile robot, algorithm, vision system, research, drive, control, frequency response, design

The object of the study is a mobile robot for inspecting parked cars.

The purpose of the final qualification work is the development of a mobile robot designed to patrol parking areas in order to scan the state numbers of parked cars for subsequent monitoring of the state of payment for parking.

The main results of the final qualifying work:

- a review of existing license plate identification systems, as well as methods for extracting characters in an image, was carried out;
- the structure and algorithm of the mobile robot control system have been developed;
- a study of the kinematics and dynamics of the robot was carried out, the law of control of a mobile robot was formed;
- the composition of the executive systems of the mobile robot is determined;
- a neural network was developed to identify the state number of a car;
- the parameters of the control loop of the drive for turning the video camera are calculated, the analysis of the operation of the drive is carried out by modeling;
- the design of the video camera units and the wheelbase was developed, the necessary calculations were made.

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INTRODUCTION

Robotics is increasingly integrated into our lives. Now there are a huge number of types of robots: household, industrial, medical, etc., and in almost every of these areas you can find a robot on a mobile platform (mobile robot). Such robots can handle a wide range of tasks, from patrolling the area to mapping previously uncharted territory.

The popularization of mobile robots is due to the relative simplicity of both control and the introduction of additional modules, such as a technical vision system (VTS), a navigation system, etc. Moreover, the use of such systems can give the robot the property of adaptability. Note that mobile autonomous robots occupy a separate self-sufficient niche in all the current variety of devices classified as robots. For such robots, which are actually non-adaptive automata with a rigid program of actions, the existing theoretical and practical solutions make the task of designing such devices purely technical.

Mobile autonomous robots have only recently become widespread, and therefore there are many problems in this area in the development of approaches to the creation of a structure. However, for all mobile autonomous robots, the following features are characteristic:

– an on-board computer with a control program responsible for the behavior of the robot and the fulfillment of assigned tasks;

– autonomous power supply system;

– drives responsible for the movement of the robot in a given environment;

– a set of executive mechanisms;

– a set of sensors that ensure the autonomy of the robot in decision-making;

– interface for communicating with the operator (control panel and displaying information about the status of the robot, etc.), which can be remote using wireless communication.

Based on the above material, we can conclude that mobile robots can perfectly replace a person in the tasks of patrolling, research and tracking.

An example of such a task is the automation of parking lots. Now, in order to track violators of the parking regime, a human parking inspector needs to independently drive around and mark the cars. In this paper, it is proposed to replace a person with a mobile robot.

Technical task

It is required to design a mobile robot that will perform the task of inspector supervision of cars parked in the corresponding zone. To do this, it is necessary to develop an algorithm for the operation of the robot, as well as to select or design its individual subsystems, such as a vision system and a control system for the robot's actuators. The mobile robot must meet the following requirements:

- The control algorithm should be universal without being tied to a specific area, taking into account the possible occurrence of malfunctions, as well as tracking obstacles along the route;
- The vision system must be able to distinguish an uncontaminated license plate in normal weather conditions;
- The overshoot of the video camera drive control system should not exceed 20%, the transition process time should be no more than 3 (three) seconds in order to ensure the speed and efficiency of the vision system;
- The design of the camera rotation unit, as well as the drive wheel units, should provide ease of assembly and maintenance of the corresponding components of the robot, the robot body should provide access to all components of the product.

The objectives of this project:

- Development of the structure of the mobile robot control system;
-Determination of the mobile platform control law based on its kinematics and dynamics;
- Development of a mobile robot control algorithm;

-Design of a vision system, including calculation and simulation of the drive for turning the video camera;

- Designing the design of the drive for turning the video camera.

RESEARCH PART

1.1. Overview of issues

Inspection of paid parking lots is a monotonous, exhausting and dangerous job, since the inspector is forced to perform monotonous actions throughout the working day, being close to the road without the possibility of rest.







An analysis was made of existing license plate identification products on the market. The result showed that such products have a high cost. The localization and license plate recognition algorithms used are not published: only a few companies name their types. For recognition, template algorithms and neural-like algorithms are usually used. A significant limiting factor for the purpose of use is the processing of the image of a standing car in a constantly changing characteristics of the street environment, in which the program is able to recognize / localize the license plate on

a standing vehicle. Among others, such circumstances as: 1) polluted, damaged numbers hinder the recognition/localization of license plates; 2) poor lighting; and 3) awkward shooting angle.







1.1.1. Types of registration numbers for vehicles

There are 20 types of Russian license plates, which contain both large and small numbers and letters; are both positive and negative (in terms of background). Depending on the license plates used, vehicles are divided into the following groups:

1 – vehicles owned by legal entities and citizens of the Russian Federation, legal entities and citizens of foreign states, except for those classified in group 3, as well as stateless persons;

2 – vehicles of military units and formations under the

jurisdiction of the Russian Federation and formed in accordance with the current legislative acts;

3 – vehicles belonging to diplomatic missions, consular offices, international (interstate) organizations;

4 – vehicles temporarily allowed to participate in road traffic;

5 – vehicles belonging to the internal affairs bodies of the Russian Federation.

Vehicles of the 1st group

Install the following types of registration plates (Figure 1):



Figure 1 – Types of registration plates of the 1st group

1 – for cars, trucks, passenger cars and buses (except for those classified as type 1B);

1A – for cars of officials according to the list determined by the Government of the Russian Federation (special registration plates);

1B – for cars used for the carriage of passengers on a

commercial basis, buses, trucks equipped for the carriage of more than eight people (except if the said carriage is carried out for the own needs of a legal entity or individual entrepreneur);

2 – for car trailers (including rear trailers for motorcycles and scooters) and semi-trailers;

3 – for tractors, self-propelled road-building and other machines and trailers (semi-trailers) for them;

4 – for motorcycles, scooters, mopeds and motonarts.

Vehicles of the 2nd group

Install the following types of registration plates (Figure 2):

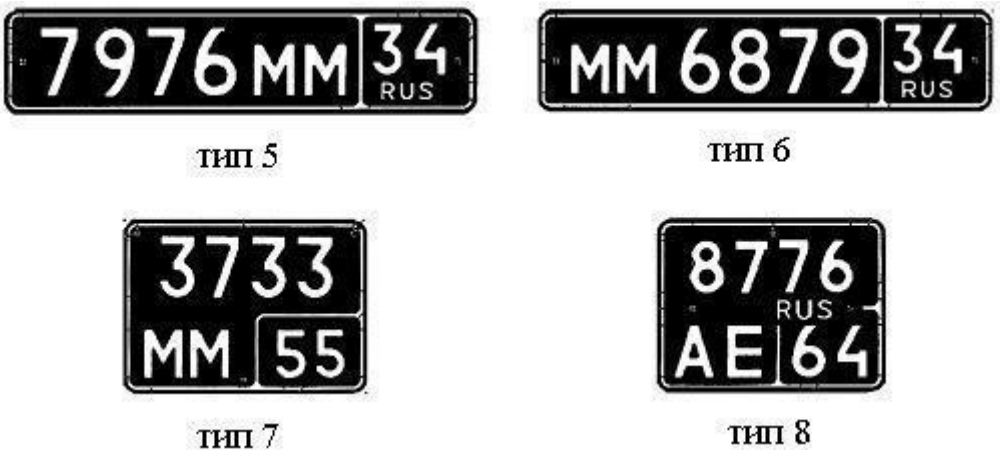


Figure 2 – Types of registration plates of the 2nd group

1 – for cars, trucks, utility vehicles and buses;

2 – for car trailers (including rear trailers for motorcycles and scooters) and semi-trailers;

3 – for tractors, self-propelled road-building and other machines and trailers (semi-trailers) for them;

4 – for motorcycles, scooters, mopeds and motonarts.

Vehicles of the 3rd group

Install the following types of registration plates (Figure 3):



тип 9 тип 10

Figure 3 – Types of registration plates of the 3rd group

1 – for cars of heads of diplomatic missions;

2 – for cars, trucks, utility vehicles and buses of diplomatic missions, consular offices, international (interstate) organizations and their employees accredited with the Ministry of Foreign Affairs of the Russian Federation;

Vehicles of the 4th group

Install the following types of registration plates (Figure 4):



тип 16 тип 17 тип 18

тип 19

Figure 4 – Types of registration plates of the 4th group

1 – for cars, trucks, utility vehicles, buses and other vehicles;

2 – for cars, trucks, utility vehicles, buses and other vehicles of military units and formations under the jurisdiction of the Russian Federation;

3 – for tractors, self-propelled road-building and other machines and trailers (semi-trailers) for them;

4 – for cars, trucks, passenger cars, buses and other vehicles that permanently leave the Russian Federation, as well as for other cases determined by the Ministry of Internal Affairs of the Russian Federation.

Vehicles of the 5th group

Install the following types of registration plates (Figure 5):



Figure 5 – Types of registration plates of the 5th group

1 – for cars, trucks, utility vehicles and buses;

2 – for car trailers (including rear trailers for motorcycles and scooters) and semi-trailers;

3 – for motorcycles.

In addition, a sufficient number of cars from the countries of near and far abroad are constantly present on the territory of Russia. Several Russian companies offer various license plate reading solutions from software modules to complete

systems consisting of image capture equipment, hardware module and software with a user-friendly interface.

1.1.2. General architecture of license plate recognition software

The license plate reading system consists of the following hardware and software modules (Figure 6):

- camcorder;
- video capture card;
- number localization module;
- recognition module;
- external database.

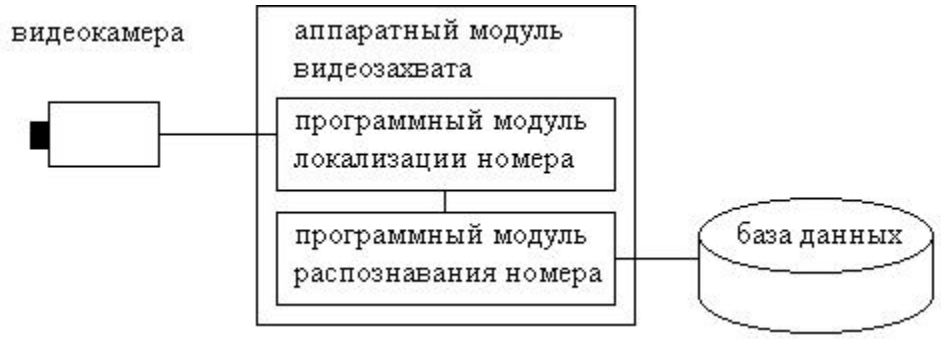


Figure 6 – General architecture

The image from the video camera is fed to the input of the localization algorithm. The software detector finds the car. Then some algorithm determines the position of the license plate. After that, the selected number is recognized by the optical character recognition program.

The database, depending on the tasks assigned to the system, may have a different scheme. The main tasks are: fixing the number, date and time of the appearance of the car in the camera's field of view.

1.1.3. Existing license plate solutions

Software " AUTO-Inspector "

"AUTO-Inspector" - a special hardware and software module for registration and recognition of license plates of the company "STB-Service" operates as follows. A TV camera is installed above the controlled lane. The camera is connected to the AUTO-Inspector system, the software of which detects the appearance of a car in the frame, selects a frame with the optimal size and clarity of the license plate, and recognizes the license plate from the frame. The database stores this still image, or the entire video clip associated with the given vehicle, as well as the recognized vehicle number, date and time of the vehicle's passage.

System Capabilities:

- simultaneous recognition of several license plates in one control zone;
- when a number from the list is found (for example, a list of stolen cars), "AUTO-Inspector" notifies the operator about this (beeps);
- the presence of an archive and the ability to work with it: printing an image of a car, sorting data in the database according to specified criteria;
- all types of Russian (single-line) numbers and some types of foreign ones are recognized;
- the ability to adapt to the standards of numbers of any country;
- the module successfully works in any weather conditions;
- effectively interacts with various security systems (CCTV, access control);
- freeze-frames of license plates are stored in the archive indicating the exact time of the car's passage;
- creation of a database of license plates;
- creation of network systems in territories of great extent;
- "live video";
- every passage, entry / exit of the vehicle is recorded;

- it is possible to create a database from special still images from 2 TV cameras (frontal picture of the car and side view);
- connection to the traffic light module, barrier, automatic gate.

License plate recognition technology consists of the following steps:

1.) the original image is reduced to a form that does not depend on such image registration conditions as: degree of illumination, uneven distribution of brightness from light sources, defocusing, noise, color unevenness of characters (uneven coloring, dirt, dust, glare), the presence of drawings or other graphics on the license plate substrate;
2.) on the resulting image, a "fast" algorithm highlights areas that may contain a number - in these areas, a more "fine" analysis is carried out based on the formal representation of the scale characteristics of the license plate and its selection;
3.) reduction to the standard size of the graphic image of the license plate, selection of characters and their recognition. The recognition algorithm analyzes characters according to key characteristics independent of the scale, font used, geometric distortion by optics, dirt sticking and gaps;
4.) refinement of recognition results based on information about the number type and results from previous frames;
5.) the vehicle number is recognized and sent to other system modules for decision making.

The result of the work is a line with a recognized number plate and a freeze frame with the image of the car (Figure 7) sent to the database.



Figure 7 – Freeze frame with a line containing a number

Auto-Intellect software

ITV has developed a license plate recognition system called Auto-Intellect.

The Auto-Intellect license plate recognition system solves the following tasks:

- increasing the efficiency of the search for stolen vehicles by 6 times, contributes to the detention of a car that has disappeared from the scene of an accident and other search activities;
- the license plate recognition system contributes to the discipline of road users;
- monitoring the congestion of intersections, key highways and traffic conditions on emergency sections of the route, as well as complex interchanges - one of the functions of the Auto-Intellect license plate recognition system;
- The Auto-Intellect license plate recognition system saves significant resources by monitoring car tunnels and bridges. A traffic jam detected by the system in time or an accident in a long tunnel can be quickly eliminated due to the prompt response of the system. For example, in the event of an accident, an ambulance or the police can be called to the scene, and during a traffic jam in the tunnels, the tunnel ventilation system can be activated;
- prompt exchange of video and audio information, database maintenance;
- coordination of various services from a single control center - including in

critical situations, in the aftermath of an accident and in providing assistance to victims;

- control of parking lots, public transport, important objects of urban infrastructure.

The principle of operation of the license plate recognition system is as follows: when a car is moving on a section of the roadway, in the field of “vision” of the TV camera, the state registration plate is automatically recognized, it is recorded in a log and checked for coincidence with the numbers in the databases. The Auto-Intellect license plate recognition system forms a database of all vehicles that have passed through the control zone, including the image, number, date, time of registration and direction of movement of each vehicle in the database.



Figure 8 – Recognition result

Features of the Auto-Intellect license plate recognition system:

- high reliability of recognition of state registration plates of vehicles moving both in the same direction and in the opposite direction;
- ease and simplicity in setup and use;
- extended network capabilities, thanks to the distributed architecture of "Intellect";
- intelligent processing of a read number (for federal and operational search, "black" or "white" lists, permission to travel "friend" / "alien", etc.);
- the ability to work from a patrol car;
- the ability to connect to pre-created databases;

- creation of operational databases and updating without stopping the system;
- formation of a sound signal to the operator to attract attention in case of coincidence with a stolen number;
- any combination of system responses;
- sampling, creating reports on various parameters;
- work with external devices - traffic lights, barriers, weight control systems;
- measuring the speed of movement using a certified radar or estimating the speed by changing the size of the image (with a rigid fixation of the video camera).

Software « SL-Traffic »

SL-Traffic is a software module for reading and recognizing license plates in real time by SpetsLab. The module works as a video filter in the GOALcity system or can be integrated into any video recording system, including third-party ones.

Features of the SL Traffic system:

- recognition of all single-line numbers issued in Russia and a number of others countries near and far abroad;
- simultaneous recognition of up to 20 license plates on one frame (a larger number of license plates simply will not fit in the frame with the required image quality);
- finding the best number from a sequence of certain numbers for one car (in case the car number was determined several times);
- accelerated work on search zones;
- the use of four number recognition algorithms to improve efficiency;
- regulation of recognition speed;
- work both with your own archive and with other databases;
- input image format: grayscale, 10 bits per pixel when digitizing, 8 bits after ADC;

- recommended frame size: 768x576;
- the minimum number height on the frame is 25 pixels;
- allowable tilt angle of the license plate image on the screen relative to the frame horizontal (achieved empirically when installing the camera by turning around its axis) - up to 5 degrees in any direction;
- allowable horizontal distortion (when the camera is installed on the side of the identified car number) - up to 30 degrees;
- allowable vertical distortion (when the camera is installed above or below the identified car number) - up to 60 degrees.

Operating principle. A video camera is installed at the checkpoint in accordance with the requirements listed above. The video signal from this camera is entered into the computer by means of a video capture card installed in it and processed in real time by the software module for reading and recognizing license plates SL-Traffic in the following sequence:

- a moving vehicle is detected in the camera coverage area;
- a search for a license plate (or several numbers) is carried out;
- the detected number is recognized;
- pictures of a passing car are taken (at the request of the user);
- the received information is transferred for registration and archiving to a database selected at the discretion of the user;
- an archive is maintained.

The user is offered four types of number recognition algorithms. The choice of the best of them is made by the user independently in order to achieve the best result in specific application conditions. The operation of the SL-Traffic software module in combination with the SpetsLab - Registration Check software is also carried out in real time and almost instantly (within one second) performs the following operations:

- carries out recognition of numbers;
- performs a search in all databases existing in the traffic police;
- when criminal information is detected, it issues a sound notification and an alarm message on the monitor screen;

- all information received is recorded in a log.



Figure 9 – SL-Traffic license plate identification module

Software "DIGNUM AUTO"

The license plate recognition system "DIGNUM AUTO" is designed for:

- detection and recognition of Russian state license plates (GNZ) of vehicles in the image received from selected channels implemented on video capture cards of the Megaframe type;
- creating a GEO database and working with it.

Functions of the license plate recognition system:

- displaying the received image on the screen;
- search for license plates on the image of the vehicle, their detection and recognition with subsequent entry into the common database of recognized GEOs;
- comparison of the recognized number with the numbers available in the database (for example, to search for a vehicle);
- saving on the hard drive of the computer a color image of a vehicle with a recognized number plate, a grayscale and a binary image of a recognized GEO;

- implementation of system settings;
- viewing the database of recognized license plates and their saved images;
- "loopback" base;
- creation of a special additional archive list filled by the user himself. Its elements are GNZ, the appearance of which in the controlled area triggers an alarm (wanted cars, cars of VIP clients, etc.).

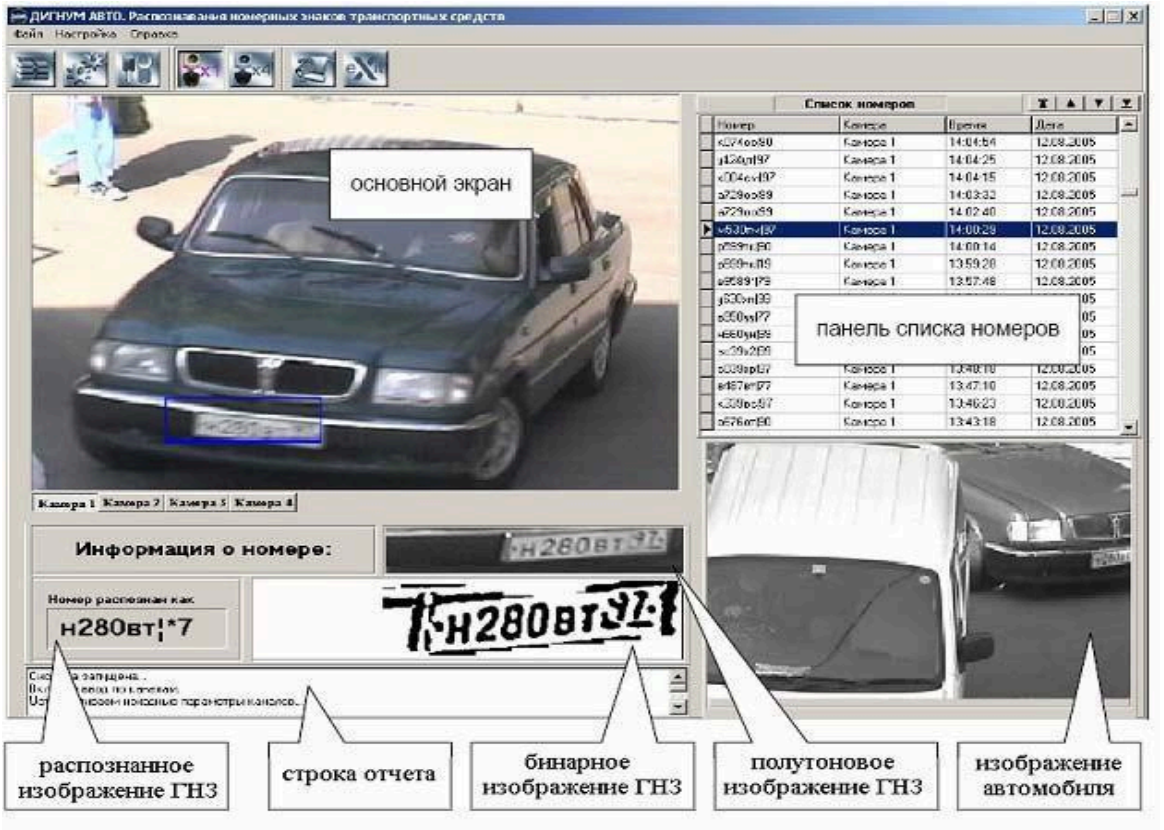


Figure 10 – Interface of the "DIGNUM AUTO" system

CarFlow II Software

Mega-Pixel LLC's CarFlow II system is based on the Mega-Frame-4 video processor (developed by MegaPixel) based on the PCI bus. The size of the processed image is 768×288 gray or color pixels.

One of the most important parameters of a license plate reading system is its speed. MegaPixel systems use original neural-like algorithms. The algorithm can

work with both front and back numbers. External start is not required. This is very important for systems with a wide field of view, since very often several vehicles can simultaneously be in the control zone at the same time. The MegaPixel algorithm is multi-zone - up to 16 license plates can be detected simultaneously. In this case, the processing speed does not depend on the number of detection zones. Detection time for CarFlow II - 60ms. After detection, the part of the image containing the number (192x24 pixels) is subjected to a pre-processing procedure: deletion of false positives of the detector, "cleaning", determination of the number type (positive or negative), magnification and binarization. False alarm removal time - 0.5ms. The total preprocessing time for one zone is 3.0ms. The final stage of the process is OCR (optical character recognition). The recognition time is approximately 20ms.

Another important parameter is the minimum allowable contrast of the license plate image. Talon states the following limitation for their system: "The difference between the average brightness level of the characters and the average brightness of the license plate background must be at least 25% of the full-scale video signal." Using this definition of contrast, it can be stated that MegaPixel systems can operate with 5% image contrast.



Figure 11 – CarFlow II system interface

1.1.4. Overview of mathematical recognition methods

In general, text recognition consists of the following procedures and methods (Figure 12):

- preprocessing;
- segmentation;
- recognition.

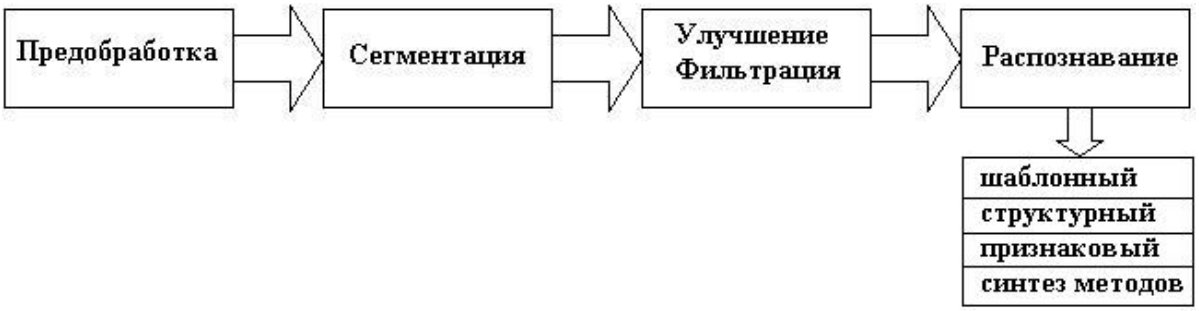


Figure 12 – Basic procedures and methods of text recognition

The preprocessing procedure is almost always used after receiving information, and is the use of averaging and histogram equalization operations, various types of filters to eliminate interference, and suppression of external noise. Segmentation refers to the process of dividing an image into individual characters. The final stage of processing is recognition. For this step, the input data is the images resulting from the denoising and segmentation process. Today, three approaches to character recognition are known – template, structural and indicative.

The template methods convert the image of a single character to a bitmap, compare it with all the templates in the database, and choose the template with the least number of pixels different from the input image. Template methods are quite resistant to image defects and have a high speed of processing input data, but they reliably recognize only those fonts whose templates they “know”. And if the recognized font differs even slightly from the reference font, template methods can

make mistakes even when processing very high-quality images!

In structural methods, an object is described as a graph whose nodes are the elements of the input object, and the arcs are the spatial relationships between them. Methods that implement this approach usually work with vector images. Structural elements are the lines that make up the symbol. So, for the letter "p" - this is a vertical segment and an arc.

The disadvantages of structural methods include their high sensitivity to image defects that violate the constituent elements. Also, vectorization can add additional defects. In addition, for these methods, in contrast to template and feature methods, effective automated training procedures have not yet been created. Therefore, structural descriptions most often have to be created manually.

In feature methods, the average image of each character is represented as an object in the n-dimensional feature space. Here, an alphabet of features is selected, the values of which are calculated when recognizing the input image. The resulting n-dimensional vector is compared with the reference ones, and the image is related to the most appropriate of them.

There are also many methods built as a synthesis of the three approaches. Below are the most popular, well-studied and often applied in practice various methods of character recognition.

1.1.4.1. Skeletal pattern recognition

First of all, the recognized character is subjected to the skeletonization (thinning) procedure. There are various methods for obtaining the skeleton of a symbol, different from each other.

Shchepin's method

For each outer and inner contour of the image, the original upper left points are found. For the next point of the contour, the configuration of its eight neighbors is considered. A point is removed if it is not a terminal point, and if, after its removal, its neighbors will still form a connected set. After the analysis of the point and its

neighbors, and the possible removal of the point, the transition to the next point of the contour is carried out in such a way as to remain on the border of the image. Next, one layer of points is removed step by step. Layers are removed until only non-removable points remain (Figure 13).

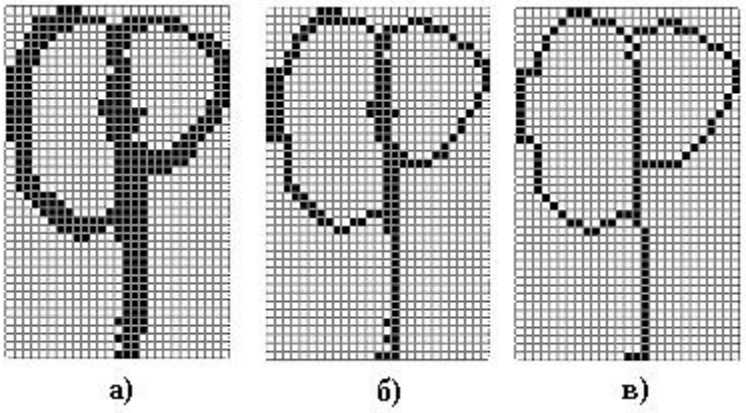


Figure 13 – Skeletonization of the letter "F", consisting of one external and two internal contours. a) the original image; b) removal of one layer; c) removal of the second layer.

Skeletonization using templates

To obtain a skeletal image, templates are used to remove extra pixels, where pixels of any color are marked with an “X” (Figure 14). In any area that matches one of the patterns, the black center pixel is removed. Several passes are made through the image until there are no pixels left to be removed.

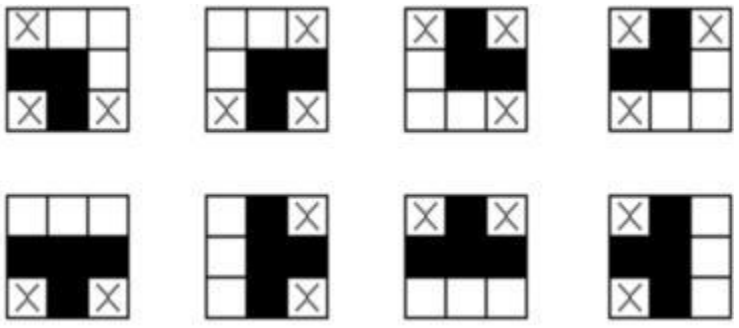


Figure 14 – Skeleton Templates

To prepare for the recognition stage in the resulting skeleton, we select the key points: the connection points of three or four edges of the skeleton and the end points:

1. We create an empty stack to store the coordinates of the beginning and end of the edges, branch points of the skeleton.
2. We enter any point of the skeleton into it.
3. As long as the stack is not empty, continue steps 4-7.
4. Pick a point from the stack.
5. We build a sequence of edges from the selected point in the image until the skeleton branches, or we reach the end point.
6. If the end point is reached or the previously marked edge is reached, then the passed path is entered into the array.
7. If the skeleton branched, then we found the junction of the edges, and the sequence of edges is entered into the array. Push the branch point onto the stack.
8. Let's move on to point 3.

In the obtained description of the skeleton, coarse preprocessing is performed, which consists in removing short lines and combining close triodes.

wave method

The method consists in analyzing the path of the spherical wave through the image (Figure 15). At each step, the displacement of the center of mass of the points that form a new generation of the wave is analyzed relative to its previous positions. The method consists of the following steps:

- building an image skeleton using a spherical wave;
- optimization of the resulting skeleton.

Image lines are tracked by tracking the movement of the center of the segment formed by the extreme points of wave generation (Figure 16, *a*). After tracking, smoothing of segments is possible.

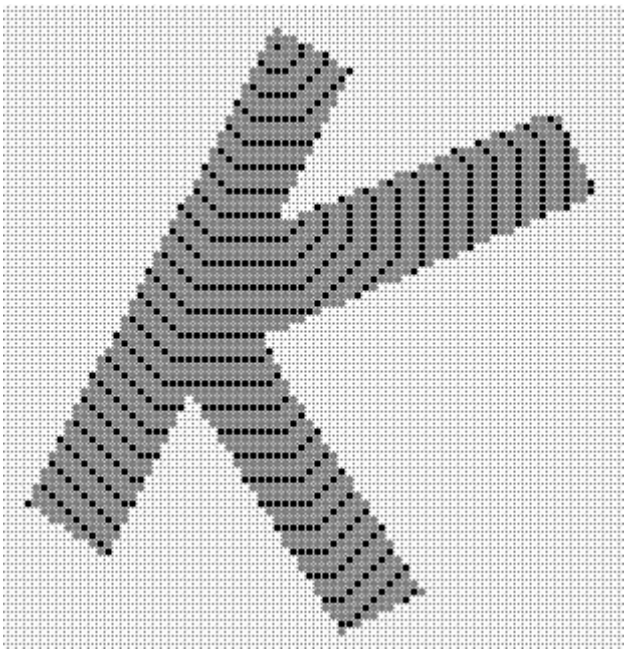


Figure 15 – The passage of a spherical wave through the image

Identification of the increase in the "width" of the wave and the division of the wave into child ones allows you to set the point of the alleged connection of the two segments. The increase in the "width" of the wave is determined by comparing the "width" of the next generation of the wave and its average value for *N* previous generations (*N* is set in advance). Moreover, we get two points *(A, B)* of the traced segment. After splitting the wave into two half-waves, we get two more pairs of points *(C,D)* and *(E,F)* . The connection point of the segments lies in the hexagon *ABCDEF* and is initially set as the center of mass of this polygon (Figure 16, *b*). The correction is assigned to the optimization of the image skeleton.

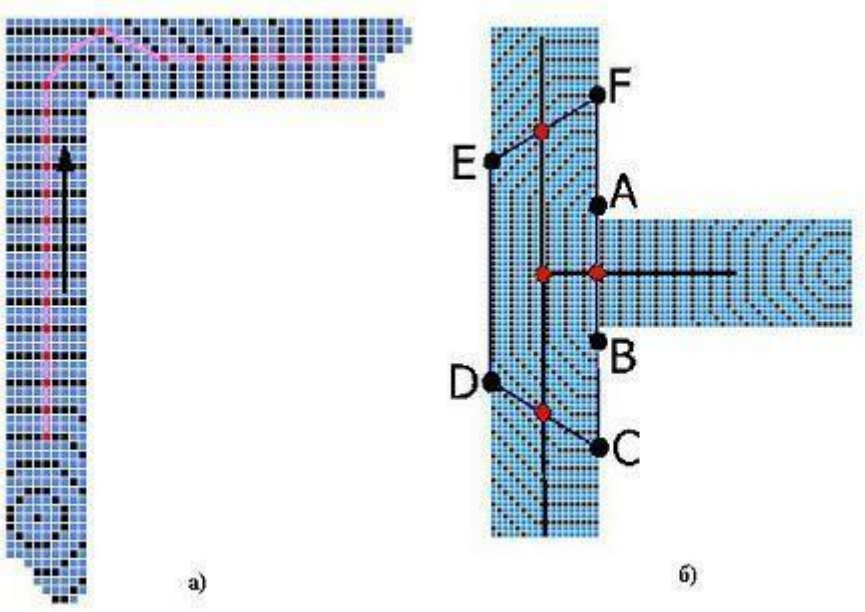


Figure 16 – a) tracking image lines, b) determining the junction of the segments

The resulting image skeleton is not optimal. This is primarily due to the fact that we are dealing with a raster image, which means that the image has distortions that are greater, the smaller the image size in symbols. To reduce the effect of distortions on the resulting skeleton, it is necessary to optimize it. In the resulting skeleton, one segment can be represented by some sequence of edges. You can get rid of this by analyzing the sequence of edges, evaluating the resulting line from a straight line. If the deviation is within acceptable limits, it is necessary to replace the sequence of edges with one.

To optimize the skeleton, the neighborhoods of the selected points of connection of the segments are examined, i.e. points where the wave splits into half-waves. The most common distortions (Figure 17, *a*)

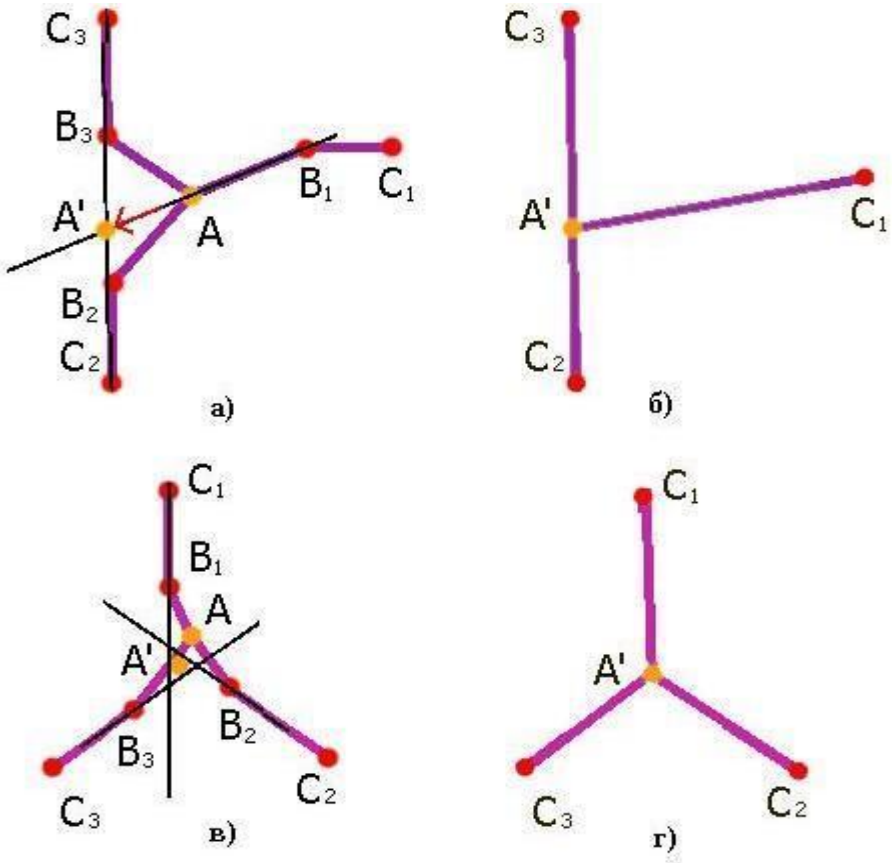


Figure 17 – Optimization of the connection point of the segments

are corrected by analyzing the segments adjacent to the selected point A (segments AB_1, B_1C_1, AB_2, B_2C_2, AB_3, B_3C_3) The analysis consists in finding such a pair C_xB_x, from (B_1C_1, B_2C_2, B_3C_3) segments C_yB_y that C_xB_x are maximally correlated with the line B_yC_y. *Then it is necessary* to move point A *to the point of intersection of lines* C_xC_y and AC_2, and then remove from point B_1, B_2 (Figure 17, *b*). Another distortion option is the case of connecting three segments at one point (Figure 17, *c*). In this case, it is impossible to find a pair of segments of a correlated line. Point A must be moved to the center of the triangle formed by lines B_1C_1, B_2C_2 and B_3C_3 · Then dots B1, B2 and B_3 must be removed from the graph (Figure 17, *d*).

self-recognition

For each singular point of the resulting skeletal representation, a set of topological features is calculated, the main of which are:

- normalized coordinates of a singular point (graph vertex);
- the length of the edge to the next vertex as a percentage of the length of the entire graph;
- normalized direction from a given point to the next singular point;
- normalized direction of entry to the point, exit from the point;
- curvature of the arc, more precisely the "left" and "right" curvature of the arc connecting the singular point to the next vertex (left and right curvature). Curvature is calculated as the ratio of the maximum distance from the points of the arc (located respectively to the left / right of the line) to the line connecting the vertices, to the length of the segment connecting the same vertices;

Figure 18 conventionally shows some of the topological features. The graph has five singular points - a0, a1, a2, a3, a4. When traversing the graph along the route a0 ==> a1 ==> a2..., the following features are conditionally shown at the vertex a1: vector R1 - direction of entry to the point, vector R2 - direction of exit from the point, vector R3 - global direction to the next singular point . The bidirectional vector h shows the value of the "left" deviation of the arc (A1,A2) from the straight line; "right" deviation is equal to zero.

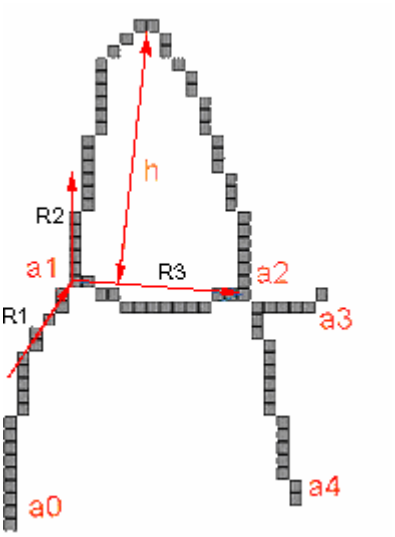


Figure 18 – An example of topological features

For some codes, the number of singular points and, accordingly, the number of topological features is too small. So, for the code corresponding to the symbol "0", there are no topological signs at all, since there is no special point. Therefore, the following additional features can be calculated and used:

- sizes and position of components and holes,
- "black" and "white" width of the upper half of the character,
- modified straight bends.

Deflections are calculated as distances from the points of the skeletal representation to the convex hull of the constructed representation. Additionally, the position of the points of maximum deflection is memorized. For some topological codes, the number of topological features can be quite large, which may require too large a set of training standards, so in some cases some of the features are used in recognition.

A symbol is determined by comparing its description with codes from the database, and the closest topological code is selected. If the character remains unrecognized after passing the recognition cycle, an attempt is made to improve the image using the following operations:

- glue the ends of the lines in directions (Figure 19); to do this, consider the directions of all end arcs of the skeletal representation, and if the directions

of any lines are similar (up to a sign) and point to each other, you can try to connect them - perhaps it was a solid line that broke due to an insufficient level of scanning or original spelling defects;

- glue the points of the skeleton located at a minimum distance from one another;
- discard the shortest line (graph arc); excessive short arcs (lines) often occur when handwriting;



Figure 19 – An attempt to improve the image of the symbol. a) the original image of the symbol; b) a symbol with glued lines

1.1.4.2. Fountain transformation

The programmers of the Russian company ABBYY have developed original technologies that improve the quality of recognition. The idea of a new way of storing knowledge about the letter – a structural spot standard – first appeared in the student works of D. Yan, K. Anisimovich and P. Senatorov. The technology of recognition with the help of structural-stained standards was called "fountain transformation" (from the English font – font).

The fountain transform combines the advantages of the template and structural methods and avoids the disadvantages inherent in each of them separately. This technology is based on the use of a structural-spot standard. It allows you to represent images as a set of spots interconnected by *n* -ary relationships that define the structure

of the symbol. These relationships (that is, the location of the spots relative to each other) form the structural elements that make up the symbol. So, for example, a segment is one type of *n* -ary relationship between spots, an ellipse is another, an arc is a third. Other relations define the spatial arrangement of the elements that form the symbol. Visually, this can be imagined in the form of tennis balls strung on a rubber band (Figure 20). The balls can move relative to each other.

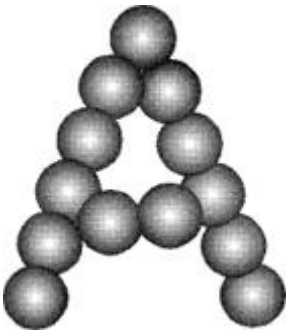


Figure 20 – Structural-stained standard of the letter "A"

Such a bunch of moving balls can be "pulled" on different images of the same character, and the system becomes less dependent on fonts and defects.

The standard specifies:

- Name;
- mandatory, prohibitive and optional structural elements;
- relations between structural elements;
- relations connecting structural elements with the describing rectangle of the symbol;
- attributes used to highlight structural elements;
- attributes used to test relationships between elements;
- attributes used to evaluate the quality of elements and relationships;
- the position from which the selection of the element begins (relations of localization of elements).

Structural elements allocated for a class of images can be initial and composite. The initial structural elements are spots, the composite ones are a segment, an

arc, a ring, a point. In principle, any objects described in the standard can be taken as composite structural elements. In addition, they can be described both in terms of the original and in terms of other constituent structural elements.

Relationships between structural elements are used as relations, which are determined either by the metric characteristics of these elements (for example, <length is greater>), or by their relative position on the image (for example, <to the right>, <contacts>).

When specifying structural elements and relations, concretizing parameters are used that allow you to extend the definition of a structural element or relation when using this element in the standard of a particular class. For structural elements, specifying parameters can be, for example, parameters that specify the range of permissible orientation of the segment, and for relations, parameters that specify the maximum permissible distance between the characteristic points of structural elements in relation <contacts>.

Construction and testing of structural-spotted standards for classes of recognizable objects is a complex and time-consuming process. The database of images that is used for debugging descriptions should contain examples of good and bad (maximum permissible) images for each grapheme, and the images of the database are divided into training and control sets. The developer of the description preliminarily specifies a set of structural elements (splitting into spots) and the relationship between them. The image database learning system automatically calculates the parameters of elements and relationships. The resulting standard is checked and corrected according to the control sample of images of the given grapheme. According to the control sample, the recognition result is checked, that is, the quality of the confirmation of hypotheses is assessed. Recognition using a structural-spot standard occurs as follows. The reference is superimposed on the image, and the ratios between the spots selected in the image are compared with the

ratios of the spots in the reference. If the spots selected on the image and the relations between them satisfy the standard of some character, then this character is added to the list of hypotheses about the result of recognition of the input image.

1.1.4.3. Adaptive recognition

Any printed text has a primary property – the font in which it is printed. From this point of view, there are two approaches to recognition of printed text: font and non-font. Font or font-dependent algorithms use a priori information about the font in which the letters are printed. This means that the recognition program must be presented with a full sample of text printed in this font. The program measures and analyzes various font characteristics and enters them into its database of reference characteristics. At the end of this process, the Optical Character Recognition (ORC) font program is ready to recognize that particular font. This process can be conditionally called program learning. Further, training is repeated for a certain set of fonts, which depends on the application area of the program. The disadvantages of this approach include the following factors:

- the algorithm must know in advance the font that is presented to it for recognition, i.e. it must store various characteristics of that font in the database. In reality, it is impossible to cover all fonts and their modifications. In other words, this factor limits the universality of such algorithms;
- for the recognition program to work, a tuning block for a specific font is required. Obviously, this block will contribute its share of errors to the integral recognition quality assessment;

On the other hand, the font approach has an advantage, due to which it is

actively used and, apparently, will be used in the future. Namely, having detailed a priori information about symbols, it is possible to build very accurate and reliable recognition algorithms. In general, when constructing a font recognition algorithm, the reliability of character recognition is an intuitively clear and mathematically exact value. This value is defined as the distance in some metric space from the reference symbol presented to the program during the learning process to the symbol that the program is trying to recognize.

The second class of algorithms is font-free or font-independent, i.e. algorithms that do not have a priori knowledge about the symbols coming to them as input. These algorithms measure and analyze various characteristics (features) inherent in letters as such, regardless of the font and absolute size (point size) in which they are printed. In the limiting case for a font-independent algorithm, there may be no learning process. In this case, the character characteristics are measured, encoded and placed into the program database by the person himself. However, in practice, cases where such a way exhaustively solves the problem are rare. A more general way to create a feature base is to train the program on a sample of real symbols. The disadvantages of this approach include the following factors:

- the actually achievable quality of recognition is lower than that of font algorithms;
- should be considered a great success if the fontless algorithm has an adequate and physically justified, i.e. naturally arising from the main procedure of the algorithm, the coefficient of recognition reliability.

The advantages of this approach are closely related to its disadvantages. The main advantages are the following:

- versatility. This means, on the one hand, the applicability of this approach in cases where the potential variety of symbols that can enter the system is large. On the other hand, due to their ability to generalize, such algorithms can extrapolate the accumulated knowledge beyond the training set, i.e. stably recognize symbols that look far from those that were present in the training sample;

- manufacturability. The process of learning font-independent algorithms is usually simpler and more integrated in the sense that the training set is not fragmented into different classes (by fonts, sizes, etc.). At the same time, there is no need to support various conditions for the joint existence of these classes in the characteristics database (non-correlation, non-mixing, unique naming system, etc.). Manifestation of manufacturability is also the fact that it is often possible to create almost completely automated training procedures.

Consideration of both approaches in comparison with each other leads to the expediency of their combination. The purpose of the merger is obvious - to obtain a method that simultaneously combines the universality and manufacturability of the fontless approach and the high accuracy of font recognition.

Mathematical model of adaptive recognition. The following assumptions are made in the model:

- symbols of the training sample belong to a single font;
- all symbols within one cycle of adaptive recognition have the same degree of distortion;
- there is some ready-made font-independent algorithm with a certain quality of recognition;
- this model does not take into account the dependence of recognition reliability on the correlation between clusters of different letters.

The model covers two key stages of adaptive recognition: training sample character clustering and additional recognition. The model is created in order to obtain an apparatus that allows one to estimate the theoretical limit of recognition quality and reliability for given parameters of primary recognition and a measure of character distortion. The system parameters are listed below:

P is the quality of recognition obtained at the stage of primary recognition;

? – a measure of the distortion of symbols, gives a numerical expression for the number of random changes in the configuration of pixels among instances of

symbols denoting the same letter of the alphabet;

F is the final quality of recognition achievable using a font-dependent algorithm adapted to a given sample of characters;

V is the reliability of character recognition: $V = f(x, P)$, where x is the distance from the given character to the center of the cluster (ideal character).

The function f is part of a specific algorithm for calculating the distance between a character and a cluster. Assume that a function is chosen that maps the differences between a symbol and a cluster to a real positive number (distance). The main position of the model is that the distance from the symbol that came to recognition to the cluster is a normally distributed random variable with a distribution density. Then, according to the given minimum admissible reliability V min calculate the maximum distance V Vmin Xmax by which the symbol can deviate from the cluster and at which Xmax $= f$ 1 (V , P). Further, by the definition of the distribution function, we obtain:

$$X \max F = \int p(x)\, dx .0$$

This equality gives an answer to the question of what the quality of recognition will be for given reliability and measure of character distortion. From a practical point of view, the question of how close the parameters of a real cluster are to the parameters of the developed model is interesting. Let's take an arbitrary cell of the cluster. Let p be the probability of a black pixel appearing here at the next addition of a symbol to this cluster. Obviously, this probability is fixed by the model itself and depends only on the position of the cell inside the grid. Thus, the process of appearance of black pixels in a given cell satisfies the Bernoulli test scheme. In the process of

physical implementation of the hit of characters in the cluster in this cell, there is ⦸ – the frequency of hitting a black pixel here. This random variable, concentrated around *p* and, according to the central limit theorem, deviating from it according to the normal distribution law,

In this reasoning, no specific conditions are imposed on the cell, therefore, the conclusion is valid for all cells of the given cluster. Thus, it can be argued that with the indicated volume of the cluster in almost 90% of its cells, the absolute error of deviation from the model will not exceed 0.07. In fact, the probability will be even greater, because owing to the simplification of the inequality, we have obtained only a lower bound.

Scheme of work of adaptive recognition. Let's take a closer look at the scheme that combines both approaches:



Figure 21 – Scheme of work of adaptive recognition

When developing the combined recognition method, the level of one page of text was chosen as the information unit on which the method should work. Because this is a large enough unit for the collected statistics to be quite representative. For example, the number of characters on an ordinary typewritten page of text is 2000, the relative frequency of the letter “n” in Russian is 0.053; thus, on a page of text, the number of letters "n" on average is 2000 ✐ 0.053 ● 106. This is quite enough to

evaluate the statistical parameters of the sample for a given letter, clustering and building binary standards for additional recognition. The first step is the recognition of the entire page by some ready-made font-independent algorithm with a given recognition quality. All characters recognized with reliability exceeding the specified threshold are considered material for training the feature base.

The task of clustering is the task of classifying presented objects into several groups, and the number of groups is not necessarily known. Each resulting group is often referred to as a cluster. One of the methods for solving the clustering problem is the chain sweep method, we will briefly describe it. An arbitrary object from the presented set is taken as the initial one, it is assigned the number 1 and the distance 0. Then all the remaining objects are viewed. The object is selected, the distance from which to the source is minimal. It is assigned the number 2 and the corresponding distance. Then, among the remaining ones, an object is searched for, the distance from which to the already marked set of objects of two elements is minimal, and so on. – always at the next step, an object is selected, the distance from which to the already numbered objects (as the distance to the set) is minimal, it is assigned the next number and this distance. The procedure is repeated until all objects are numbered.

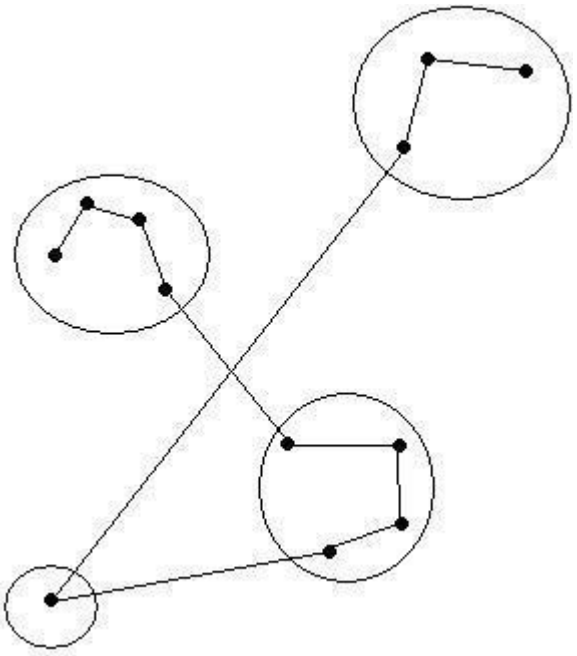


Figure 22 – An example of the operation of the chain sweep method

Consider the stage of creating a database of reference characteristics. Recall that a cluster consists of a set of bitmaps of symbols that fall into this cluster. On a raster grid of a fixed size, we put all the character rasters and sum them up inside each cell. In the corresponding cell of the cluster, we write the sum (the number of times that a black pixel was encountered in this cell). Obviously, this number is the frequency or, if normalized by the number of characters in the cluster, the probability of a black pixel in the cell. Cells in which the probability is zero are filled in differently. The distance to the nearest point with non-zero probability is recorded there. This distance will be interpreted as the "negative probability" of a pixel in that cell.

Pre-recognition is a repeated pass over the entire page in order to recognize everything that was not recognized in the first pass, and to obtain reliable recognition accuracy estimates for all characters. The scheme of the procedure is quite simple. The input received another character that requires recognition, it is represented as a bitmap. Comparing this symbol with the first standard (cluster), we obtain a numerical estimate of the similarity of the symbol with the standard. We repeat the comparison with all other standards in the database. After that, the best answer is

selected in accordance with the obtained estimates. The influence of points with "negative probabilities" on the result is enhanced, i.e. points of the symbol lying at a distance *a* or more from the positive ones significantly reduce the overall score.

1.1.4.4. Neural networks

How does a biological neural network work. The human nervous system and brain consist of neurons interconnected by nerve fibers. Nerve fibers are capable of transmitting electrical impulses between neurons. Consider the structure of a biological neuron. Each neuron has processes of two types of nerve fibers - dendrites, through which impulses are received, and a single axon, along which the neuron can transmit impulses. The axon contacts the dendrites of other neurons through special formations - synapses, which affect the strength of the impulse.

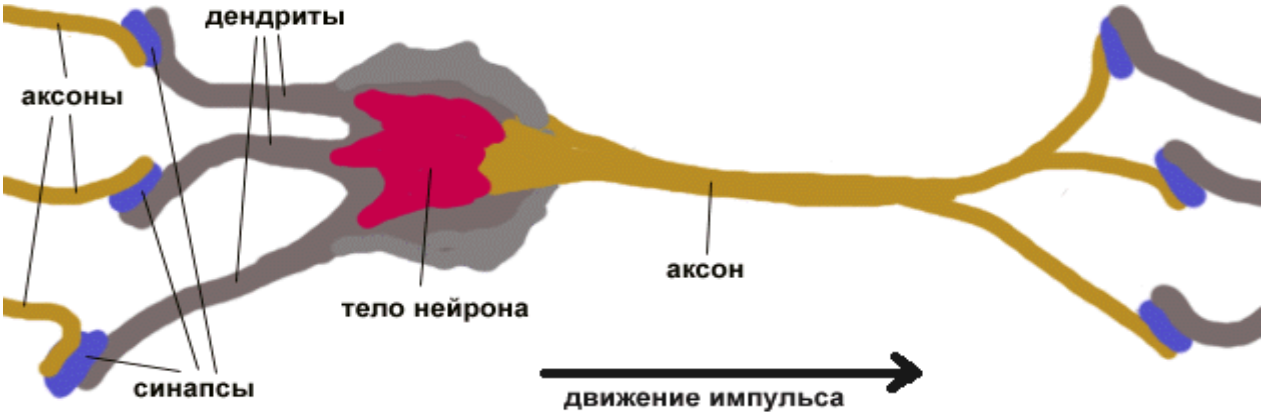


Figure 23 – The structure of a biological neuron

We can assume that during the passage of the synapse, the strength of the impulse changes by a certain number of times, which we will call the weight of the synapse. Impulses received by the neuron simultaneously through several dendrites are summed up. If the total impulse exceeds a certain threshold, the neuron is excited, generates its own impulse and transmits it further along the axon. It is important to note that the weights of synapses can change over time, which means that the behavior of the corresponding neuron also changes. It is not difficult to construct a mathematical model of the described process.

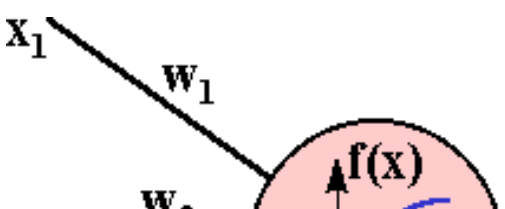


Figure 24 – Mathematical model of a neuron

Figure 24 shows a model of a neuron with three inputs (dendrites), and the synapses of these dendrites have weights w_1, w_2, w_3. Let the synapses receive impulses of strength x_1, x_2, x_3, respectively, then after passing through the synapses and dendrites, impulses arrive at the neuron w1x1, w2 x2 , w3 x3 . The neuron converts the received total impulse x ● w1x1 ✹ w2 x2 ✹ w3 x3 according to some transfer function f(x) . Force output pulse is equal to y ● f (x) ● f (w1x1 ✹ w2 x2 ✹ w3 x3) . Thus, a neuron is completely described by its weights *wk* and transfer function $f(x)$. Given a set of numbers (vector) *xk* as inputs, the neuron outputs some number *y*

Artificial neural network. An artificial neural network (ANN, neural network) is a set of neurons interconnected. As a rule, the transfer functions of all neurons in a neural network are fixed, and the weights are parameters of the neural network and can change. Some inputs of neurons are labeled as external inputs of the neural network, and some outputs are labeled as external outputs of the neural network. Submitting any numbers to the inputs of the neural network, we get some set of numbers at the outputs of the neural network. Thus, the work of the neural network is to transform the input vector into an output vector, and this transformation is given by the weights of the neural network. Almost any problem can be reduced to a problem solved by a neural network. Table 1 shows how the problem of letter recognition should be formulated in terms of a neural network.

Table 1 – Formulation of the problem of character recognition

	Letter recognition task	**Formulation for neural network**
Given	Bitmap black and white image of a letter, for example, 30×30 pixels.	Input vector of 900 binary characters (900=30x30).

Table 1 – Formulation of the problem of character recognition

Necessary	Determine what letter it is (there are 33 letters in the alphabet).	Build a neural network with 900 inputs and 33 outputs labeled with letters. If the input is the image of the letter "A", then the maximum value of the output signal is reached at the output "A". the network works similarly for all 33 letters.

1.2. Mobile robot structure

The robot consists of two main parts: a mobile platform, and a vision system consisting of a video camera and a drive for turning it. For STZ, an algorithm for highlighting image features is designed.

To develop a robot control system, its block diagram was designed (Fig. 1.4).

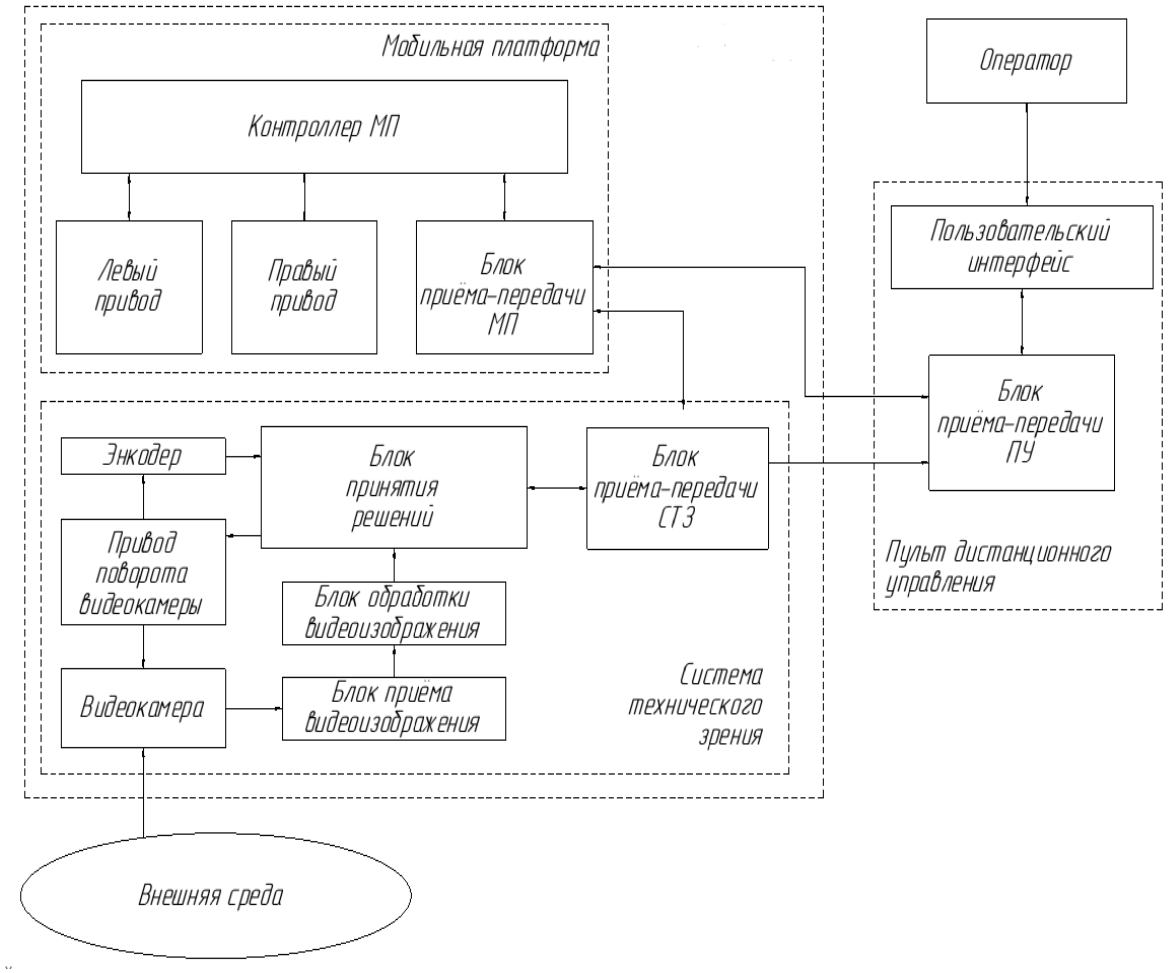


Figure 1.4 - Structural diagram of the robot

In this scheme, there are three main functional blocks: remote control, mobile platform and vision system. The image from the STZ video camera is fed to the video image receiving logic unit, after which it is processed using the developed algorithms, and based on them, and also, if necessary, based on information from the encoder of the drive for turning the video camera, the control system develops a decision on the subsequent actions of the robot, and the corresponding control signals are sent to the camera rotation drive and mobile platform driving drives. The control panel is used by the operator when human intervention is required, for example, when system errors occur or the obstruction disappearance timer expires.

1.3. Study of the kinematics and dynamics of the robot

1.3.1. Kinematic model

To form the laws of control of a mobile platform, we will study its kinematic and dynamic characteristics. Consider a flat case of robot movement (Fig. 1.10): the axes of rotation of the wheels coincide with the segment LR of the path. Associate the coordinate system O'X'Y' with the platform, placing O' in the middle of LR and directing the X' axis perpendicular to LR in the direction of movement. Then the position of the robot base as a rigid body is given by a triple of numbers φ, x, y, where φ is the angle between the X and X' axes, and x, y are the coordinates of the point O' in the absolute coordinate system $O_0X_0Y_0$. Let's introduce a homogeneous 3x3 transition matrix from O'X'Y' to OXY:

$$T = (R\ p\ 0\ 1),$$

Where$R = (\cos cos\ \varphi \quad -\sin sin\ \varphi \quad \sin sin\ \varphi \quad \cos cos\ \varphi),\ p = (x\ y)$

and represent, respectively, the orientation matrix and the position vector of the origin of the coordinate system O' in the absolute coordinate system.

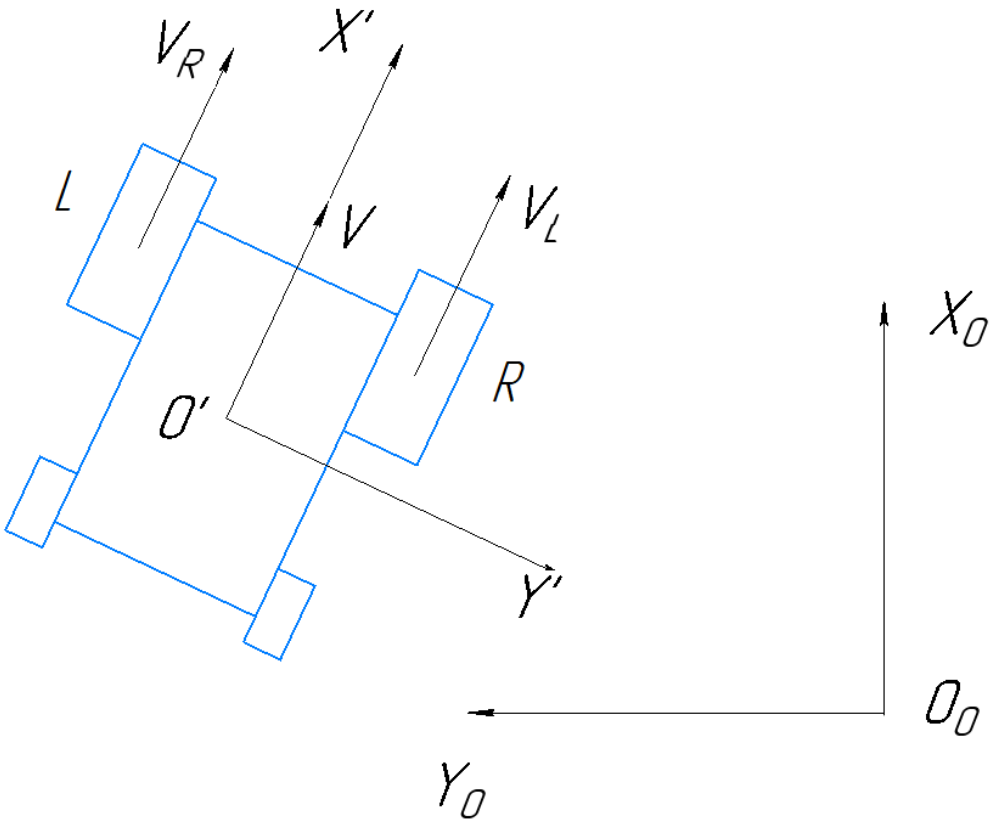


Figure 1.10 - Scheme of the movement of the mobile platform in the horizontal plane

If we designate the vectors of linear velocities of the points O', L and R as V, V_L and V_R, respectively, and through ω the angular velocity, then we can write the following relations:

$$\{V_L = V + \omega\Omega r_L;\ V_R = V + \omega\Omega r_R,$$

where matrix Ωis an orthogonal matrix that provides a rotation about an arbitrary vector by π/2 and has the form

$$\Omega = (0\ -1\ 1\ 0).$$

We write the following geometric relations:

$$\overline{r_L} = \frac{1}{2}\overline{y'};$$

$$\overline{r_R} = -\frac{1}{2}\overline{y'};$$

$$\overline{V_L} = V_L\overline{x'};$$

$$\overline{V_R} = V_R\overline{x'},$$

where $\overline{x'}$ и $\overline{y'}$ are the unit vectors of the O'X'Y' coordinate system, and V_L и V_R are the projections of the corresponding vectors onto the X' axis. The linear velocity vector of the point O', due to the relationships derived above, coincides with the X' axis. We will use this to form the control law. Then, taking into account the relations, and also bearing in mind the indicated property of the matrix Ω, after elementary transformations we obtain

$$\{V = \frac{1}{2}\left(V_R + V_L\right);\ \omega = \frac{1}{l}\left(V_R - V_L\right).$$

If we now introduce the coordinates x, y, φ, we will see that

$$\{\dot{x} = V\cos\varphi;\ \dot{y} = V\sin\varphi;\ \dot{\varphi} = \omega.$$

Substituting here the expressions for the velocities, we obtain

$$\{\dot{x} = \frac{1}{2}\left(V_R + V_L\right)\cos\varphi;\ \dot{y} = \frac{1}{2}\left(V_R + V_L\right)\sin\varphi;\ \dot{\varphi} = \frac{1}{l}\left(V_R - V_L\right).$$

These relations represent a system of non-linear differential equations of the 3rd order with respect to the phase vector with components (x, y, . φ)Scalars V_L и V_R, given in one way or another, as functions of time or phase coordinates), determine the movement of the platform. Thus, these ratios can be considered as a kinematic model of a mobile robot with two driving wheels, determining its linear and angular speed from the ratios above.

1.3.2. Dynamic Model

Before deriving the equations of motion, let's consider the dynamic constraints imposed on the platform.

The mobile robot moves on an almost flat surface, having two driving wheels of radius ρ, which rotate without slipping, and their rotation axes coincide with the

line LR. This condition is provided by an obvious expression $\dot{x}\,sin\varphi - \dot{y}\,cos\varphi = 0$,that sets restrictions on coordinates and velocities, representing one of the constraint equations, which can be geometrically represented as a velocity vector $\overline{V} = (\dot{x}, \dot{y})^T$ perpendicular to the vector $\overline{y'}$, therefore, this constraint is nonholonomic.

Let us consider the non-slip conditions, presenting the platform as a system of three solid bodies - the platform itself and two drive wheels. The position of this system is given by a set of parameters such as x, y, φ(platform position) and q_L, q_R (angles of rotation of the left and right wheels, respectively). It is known that

$$V_L = \rho\ \dot{q}_L;$$

$$V_R = \rho\ \dot{q}_R.$$

Then

$$\{\dot{x} = \frac{\rho}{2}\left(\dot{q}_R + \dot{q}_L\right) cos\varphi\ ;\ \dot{y} = \frac{\rho}{2}\left(\dot{q}_R + \dot{q}_L\right) sin\varphi\ ;\ \dot{\varphi} = \frac{\rho}{l}\left(\dot{q}_R - \dot{q}_L\right),$$

moreover, the last expression is integrable in $\varphi = \frac{\rho}{l}\left(q_R - q_L\right)$+ C. From this we deduce that the considered system has 4 generalized coordinates (for example, (x, y, q_L, q_R) and 3 degrees of freedom.

To derive the equations of motion, we use the Appel equation for a rigid body, from which it follows that

$$S = \frac{1}{2} tr\left(\ddot{T} H \ddot{T}^T\right),$$

where H is the inertia matrix, which has the form

$$H = \sum m_v \rho_v \rho_v^T = \begin{pmatrix} I_{xx} & I_{xy} & S_x \\ I_{yx} & I_{yy} & S_y \\ S_x & S_y & m \end{pmatrix},$$

where I_{ij} are second order moments, S_i = first order moments.

Based on the design features of the robot, the moments of inertia of the wheels are much less than the corresponding moments of the platform, so its inertia matrix has the form

$$H = \left(I_{xx}\,0\,0\,0\,I_{yy}\,0\,0\,0\,m\right),$$

where m is the mass of the platform.

Then we get for a platform with a distance b between the center of mass and the axle of the wheels

$$S = \frac{1}{2}\left[\left(\dot{\varphi}^4 + \ddot{\varphi}^2\right) i_z + m\left(\ddot{x}^2 + \ddot{y}^2\right)\right] + bm\left[\ddot{x}\left(\ddot{\varphi}\,sin\varphi + \dot{\varphi}^2 cos\varphi\right) + \ddot{y}\left(\dot{\varphi}^2 sin\varphi + \ddot{\varphi}\right.\right.$$

or

$$S = \frac{1}{2}\left[\left(\dot{\varphi}^4 + \ddot{\varphi}^2\right) i_z + \frac{m\rho^2}{4}\left(\ddot{q}_R^{\,2} + \ddot{q}_L^{\,2}\right)\right] + \frac{\rho}{2}\dot{\varphi}^2\left(\ddot{q}_L + \ddot{q}_R\right) - \frac{\rho}{2}\dot{\varphi}\ddot{\varphi}\left(q_R + \dot{q}_L\right).$$

In accordance with the Appel equation

$$\frac{\partial S}{\partial q_R} = Q_R;$$

$$\frac{\partial S}{\partial q_L} = Q_L.$$

If we accept that the generalized forces Q_R и Q_L are the moments τ_R and τ_L developed by the wheel drives, we get

$$\{m\dot{V} = -\,bm\omega^2 + \frac{1}{\rho}\left(\tau_R + \tau_L\right);\; i_z\dot{\omega} = -\,bm\omega V + \frac{l}{2\rho}\left(\tau_R - \tau_L\right).$$

We present in a form convenient for modeling:

$$\{\dot{x} = V\,cos\varphi;\; \dot{y} = V\,sin\varphi;\; \dot{\varphi} = \omega;\; \dot{V} = -\,b\omega^2 + \frac{1}{\rho m}\left(\tau_R + \tau_L\right);\; \dot{\omega} = -\frac{bm\omega V}{i_z} + \frac{l}{2\rho i_z}$$

Let us consider the case when the wheels of the platform are directly controlled by DC motors (the presence of servo drives does not have fundamental differences). Considering that the DCT $L\dot{I} + RI + K_w\omega_m = U$ equation ω_w has the ω_w i form ω_m developed by the engine, $\tau = K_M I$, we get

$$\dot{\tau} = -\frac{R}{L}\tau - \frac{K_M K_w i}{L}\omega_w + \frac{K_M}{L}U.$$

Then for the left and right wheels

$$\{\dot{\tau}_L = -\frac{R}{L}\tau_L - \frac{K_M K_w i}{L}\omega_L + \frac{K_M}{L}U_L;\ \dot{\tau}_R = -\frac{R}{L}\tau_R - \frac{K_M K_w i}{L}\omega_R + \frac{K_M}{L}U_R.$$

1.3.3. Formation of the control law

Considering that the angular speeds of the wheels are related to the linear and angular speeds of the platform as

$$\omega_L = \frac{1}{\rho}\left(V + \frac{\omega l}{2}\right),$$

$$\omega_R = \frac{1}{\rho}\left(V - \frac{\omega l}{2}\right),$$

Let's take the following method of forming the control voltages applied to the drives of the driving wheels of the mobile platform:

$$U_L = U_d - U_\varphi;$$

$$U_R = U_d + U_\varphi,$$

where U $_d$ \u003d const is the voltage that provides the given linear speed of movement, and U $_\varphi$ is the voltage that controls the angular speed.

We write the following control law:

$$U_\varphi = -k_1\varphi + k_2(-y - y^*),$$

where k $_1$, k $_2$ are some parameters, and φ, y and y* are found from the conditions indicated in Figure 1.11.

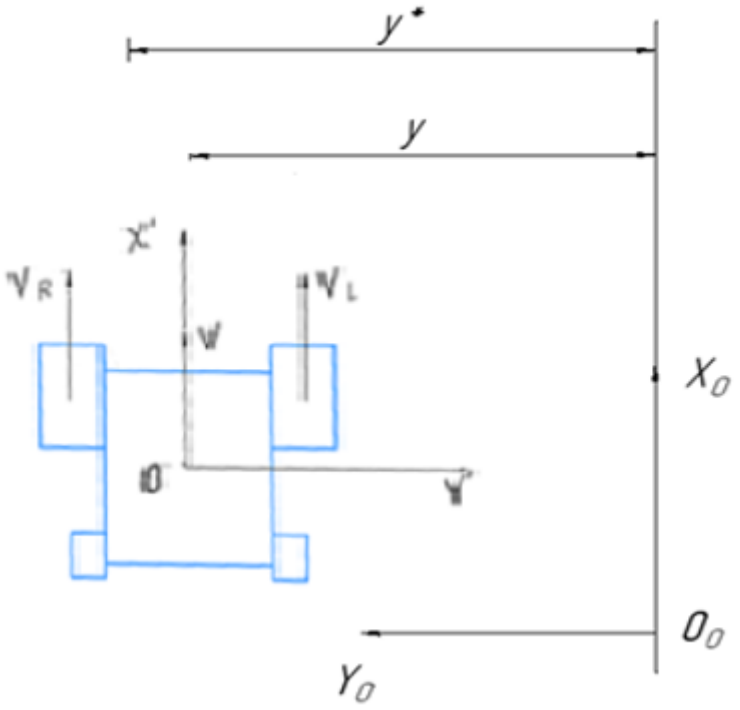


Figure 1.11 - Scheme for calculating the law of control of a mobile platform moving along the curb.

Substituting it into the force equations for the left and right wheels and changing the notation, we obtain the control law:

$\{\dot{x} = V\cos\varphi\,;\ \dot{y} = V\sin\varphi\,;\ \dot{\varphi} = \omega\,;\ \dot{V} = -b\omega^2 - AV - DU_d\,;\ \dot{\omega} = C\omega V - D\omega - E$

where $\mu = \frac{2i_p^2 k_M k_{тг} k_y}{R\rho}$, $\delta = \frac{2i_p k_M k_y}{R}$,

$A = \frac{2\mu}{\rho m}$, $B = \frac{2\delta}{\rho m}$, $C = \frac{bm}{i_z}$, $D = \frac{l^2\mu}{2\rho i_z}$, $E = \frac{l\delta}{\rho i_z}$.

In this case, after finding the stability of the system of equations in deviations relative to a given trajectory, we obtain

$0 < \frac{k_2 V^*}{D} < k_1$

$\frac{p^3}{27} + \frac{q^2}{4} \leq 0$,

Where

$$p = -\frac{b^2}{3a^2} + \frac{c}{a},\ q = \frac{2b^3}{27a^3} - \frac{bc}{3a^2} + \frac{d}{a},\ a = 1,\ b = D,\ c = E\,k_1,\ d = E\,k_2 V^*.$$

1.4. Choosing a Camera for the Inspector Robot

One of the main parameters of a camera is its resolution in megapixels (MP). You can roughly calculate the required value using the formula:

$$Resolution = \left(\frac{Obcect\ size}{target\ size}\right)^2$$

In our case, the size of the object in the photo is equal to the size of the car. Because there are a large number of types of machines in the world and their sizes are not standardized, we will take the parameter *object size* = 4м^2

The size of a car number in the Russian Federation, on the contrary, has standardized dimensions: 520mm x 117mm. Thus the parameter *target size* = 0.06 м^2.

Thus:

$$Resolution = \left(\frac{4}{0.06}\right)^2 = 0.4\ \text{Мп}$$

Also, since work can be carried out both in the daytime and at night, it is necessary that the camera supports the “day / night” mode

The next important parameter is the camera angle. Here it is worth saying that in many ways the viewing angle will affect the logic of the system control algorithm, so in our task we can set a certain range (in degrees): from 100 to 130 degrees.

Summing up all the calculations and reasoning, the B1020 camera from Imprex was chosen (Fig. 1.).



Figure 1. Image of the B1020 camera

The technical characteristics of interest to us are presented in Table 1.

Table 1. B1020 Camera Specifications

Parameter	Meaning
Mass, *m*	0.5 kg
Resolution _	1 MP
Dimensions	90x70x150 mm
Viewing angle	110^0

1.5. Calculation of the drive for turning the camera

1.5.1. Energy calculation of the drive motor

At this stage, it is necessary to select the SPK drive motor. The criterion by which we will look for it - the engine power must be greater than or equal to the power of the process

$$P_{\text{двиг}} \geq P_{\text{проц}}$$

Process power is determined by the formula:

$$P_{\text{проц}} = P_{\text{вых}} = \frac{T_{\text{вых}} \omega_{\text{вых}} k_{\text{з}}}{\eta}$$

where $P_{вых}$ is the power on the drive output shaft, is $T_{вых}$ the torque on the drive output shaft, $\omega_{вых}$ is the angular velocity on the drive output shaft, η= 0.65 is the transmission efficiency, $k_з = 1.5$ is the safety factor.

Now we calculate the moment on the output shaft:

$$T_{вых} = F_t R$$

Where F_t is the traction force of the drive, R is the radius of the working body;

Calculate the traction force by the formula:

$$F_t = mgt$$

In our case, m is the mass of the chamber, t = 0.4 is the coefficient of friction in the bearings, then:

$$F_t = 0.5 \cdot 0.4 \cdot 10 = 2 \text{ Н}$$

Knowing the traction force, we can find the output moment:

$$T_{вых} = 2 \cdot 0.15 = 0.3 \text{ Нм}$$

It remains to find the required angular velocity:

$$\omega_{вых} = \frac{\pi \cdot n}{30}$$

Here n is the speed on the output shaft in rpm. In our task, there is no restriction on the speed of rotation of the camera, so let's take (taking into account the margin) n = 10 rpm, then

$$\omega_{вых} = \frac{\pi \cdot n}{30} = 1.04 \text{ rad/s}$$

Now we can calculate the required power on the motor output shaft:

$$P_{вых} = \frac{0.3 \cdot 1.04 \cdot 1.5}{0.65} = 0.72 \text{ Вт}$$

Knowing the required minimum power, we will select an engine from the Maxon motor catalog. Maxon EC-max 16 will be the most suitable for our task (Fig. 2, Fig. 3).



Figure 2 - Maxon EC-max 16 engine

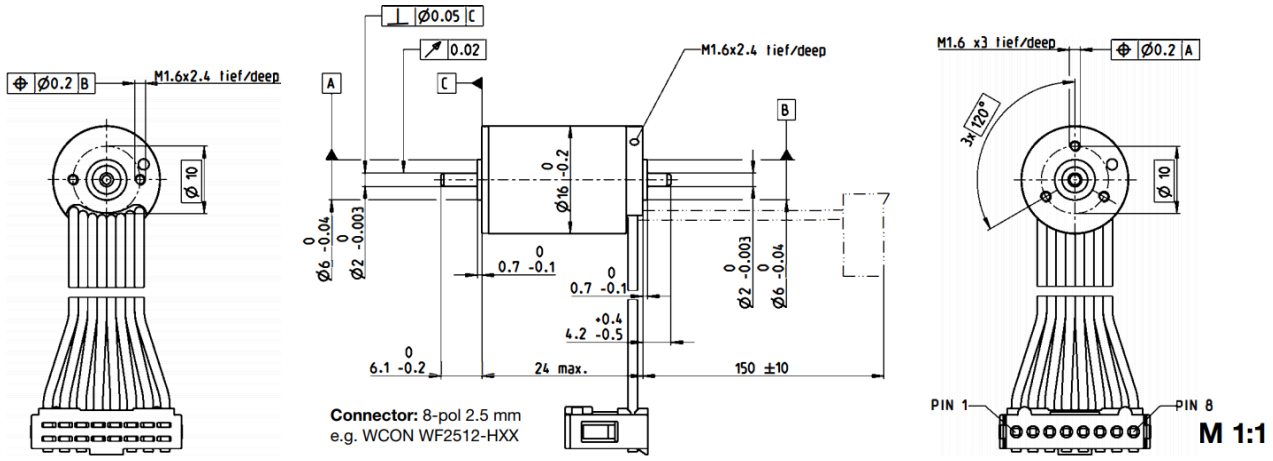


Figure 3 - Dimensional drawing of the engine

Table 1 - Main characteristics of the selected engine

Rated voltage, V	12
Idling speed, rpm	13500
No-load current, mA	60.2
Rated speed, rpm	5840
Rated torque, mNm	3.23
Rated current, A	0.652
Starting torque, mNm	5.95
Starting current, A	0.762

The gearbox that is optimal for the purposes of this project is Planerary Gearhead GP 16 C Ø16 mm (Fig. 4.5):



Figure 4 - Planerary Gearhead GP 16 C

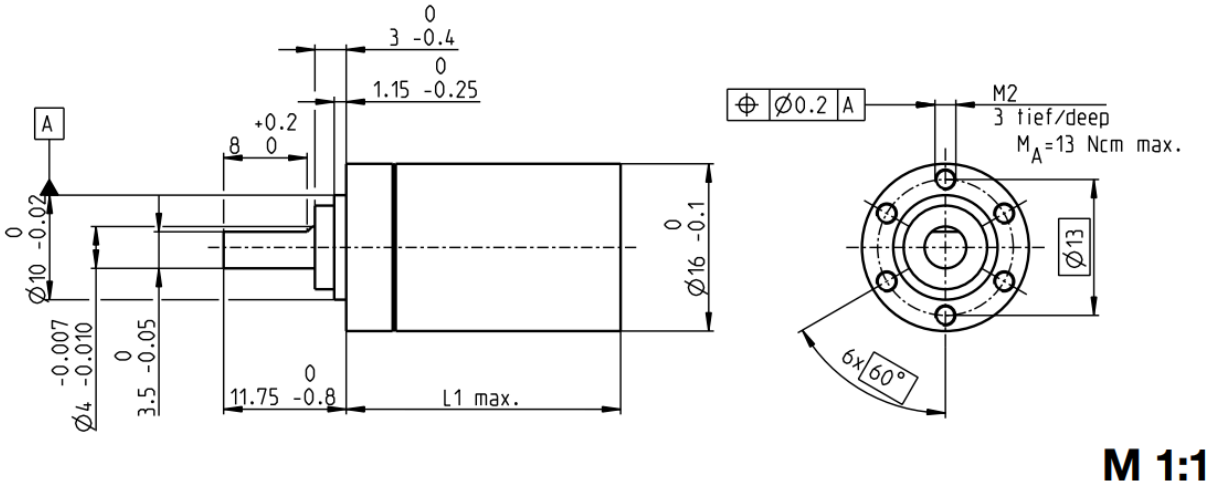


Figure 5 - Dimensional drawing of the gearbox

Table 2 - Main characteristics of the selected gearbox

Gear ratio	690:1
Number of steps	4
Maximum, continuously perceived moment, Nm	0.5
Maximum overload moment, Nm	0.75
Efficiency, %	65
Maximum radial load on the output shaft, N	80
Maximum input speed, rpm	12000

The selected motor has built-in Hall sensors, so the position of the motor shaft can be read directly from the motor without installing an encoder. However, if the resolution of the internal Hall sensors is not sufficient, an Encoder MR, Type ML, 512 CPT, 3 Channels, with Line Driver compatible with this engine can be used (Fig. 6).

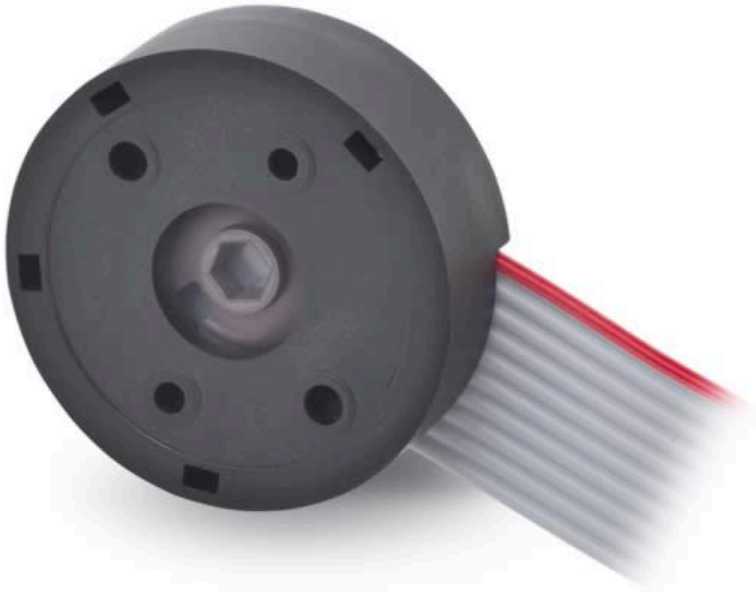


Figure 6 - Maxon Encoder

Table 3 - Main characteristics of the selected encoder

Counter value per turn	512
Number of channels	3
Maximum perceived speed, rpm	37500
Supply voltage, V	4.7…5.2

To control the motor-reducer, it is proposed to use the ESCON Module 50/4 EC-S, 4-Q Servocontroller for sensorless EC motors, 4/12 A, 10-50 VDC compatible controller (Fig. 7).

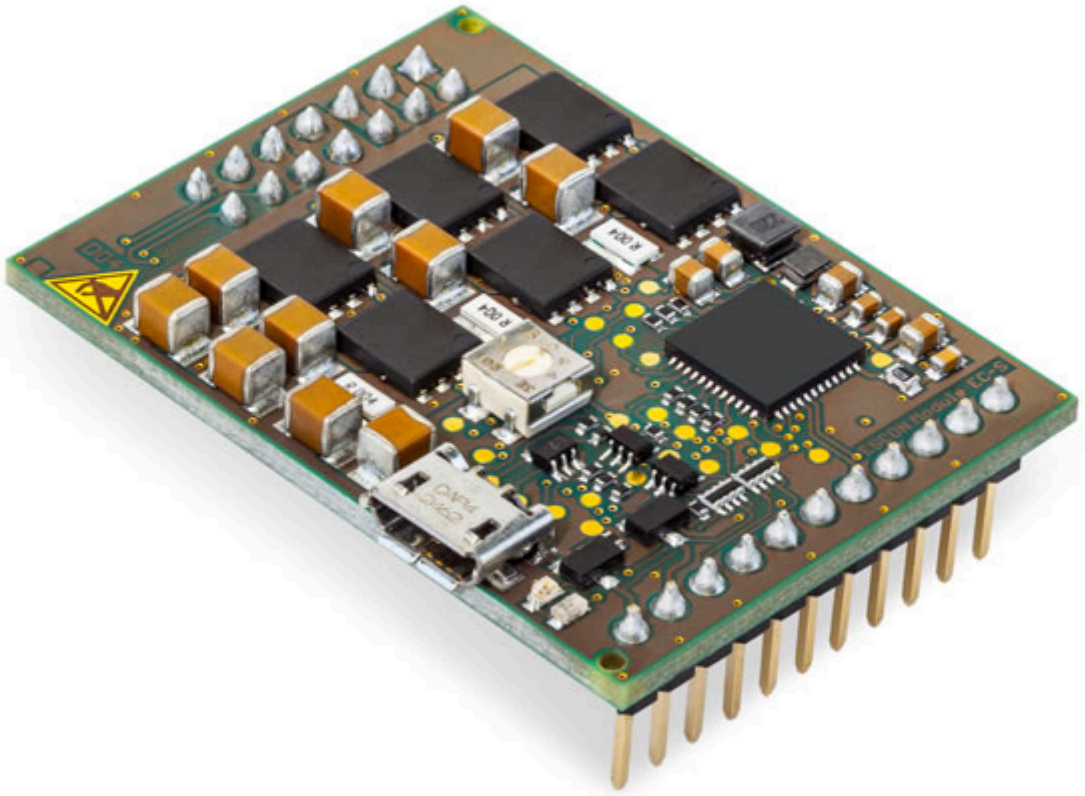


Figure 7 - Controller ESCON Module 50/4 EC-S

Table 4 - Main characteristics of the selected controller

Maximum engine power, W	200
Operating voltage, V	10…50
Maximum output current, A	12
Operating output current, A	4
Maximum PWM signal frequency, kHz	53.6

1.5.2 Adjustment calculation

Ensure: independence of the steady-state speed of the drive from the external torque:

$f_{pcmin} = 70$ - minimum speed loop bandwidth

M_{skmax} \u003d 2 - maximum oscillation of the speed loop

M_{pmax} \u003d 1.3 - maximum oscillation of the position loop

Drive calculation. Calculation of the parameters of the invariable part

a) Motor and mechanical load parameters

Расчитаем электромеханическую постоянную времени двигателя:

$$T_{м_мин} := \frac{J_{min} \cdot R_{я}}{K_{м} \cdot K_{w}} \qquad T_{м_мин} = 2.558 \times c0^{-3}$$

$$T_{м_ср} := \frac{J_{ср} \cdot R_{я}}{K_{м} \cdot K_{w}} \qquad T_{м_ср} = 3.083 \times c0^{-3}$$

$$T_{м_макс} := \frac{J_{max} \cdot R_{я}}{K_{м} \cdot K_{w}} \qquad T_{м_макс} = 3.608 : c10^{-3}$$

$$J_{min} := J_{д} + J'_{нmin} = 2.73 \times 10^{-3} \text{ кг*м^2}$$

$$J_{max} := J_{д} + J'_{нmax} = 3.85 \times 10^{-3} \text{ кг*м^2}$$

$$J_{ср} := \frac{J_{min} + J_{max}}{2} = 3.29 \times 10^{-3} \text{ кг*м^2}$$

Calculate the electromechanical time constant of the motor:

$$T_{м_мин} := \frac{J_{min} \cdot R_{я}}{K_{м} \cdot K_{w}} \qquad T_{м_мин} = 2.558 \times c0^{-3}$$

$$T_{м_ср} := \frac{J_{ср} \cdot R_{я}}{K_{м} \cdot K_{w}} \qquad T_{м_ср} = 3.083 \times c0^{-3}$$

$$T_{м_макс} := \frac{J_{max} \cdot R_{я}}{K_{м} \cdot K_{w}} \qquad T_{м_макс} = 3.608 : c10^{-3}$$

Consider the polynomial A(s), which takes into account the inertial properties of the motor and the converter, and substitute the initial conditions and electromechanical time constants into it:

$$A_{мин}(s) := (1 + T_y \cdot s) \cdot \left(1 + T_{м_мин} \cdot s + T_{м_мин} T_э \cdot s^2\right)$$

$$A_{ср}(s) := (1 + T_y \cdot s) \cdot \left(1 + T_{м_ср} \cdot s + T_{м_ср} \cdot T_э \cdot s^2\right)$$

$$A_{макс}(s) := (1 + T_y \cdot s) \cdot \left(1 + T_{м_макс} \cdot s + T_{м_макс} \cdot T_э \cdot s^2\right)$$

$$A_{мин}(s) \text{ float , } 3 \rightarrow (0.0004 \cdot s + 1.0) \cdot \left(0.00256 \cdot s + 0.0000205 \cdot s^2 + 1.0\right)$$

$$A_{ср}(s) \text{ float , } 3 \rightarrow (0.0004 \cdot s + 1.0) \cdot \left(0.00308 \cdot s + 0.0000247 \cdot s^2 + 1.0\right)$$

$$A_{макс}(s) \text{ float , } 3 \rightarrow (0.0004 \cdot s + 1.0) \cdot \left(0.00361 \cdot s + 0.0000289 \cdot s^2 + 1.0\right)$$

Calculation of current loop parameters (PI controller). We take the time constant of integration of the current controller equal to the larger of Te and Tu:

$$\tau_{рт} := T_э = 8 \times 10^{-3} \quad c$$

Total current loop gain excluding back electromotive force (MO setting):

$$r_T := \frac{1}{2T_y} = 1.25 \times 10^3 \quad c^{-1}$$

Current loop gain:

$$K_{рт} := \frac{r_T \cdot R_я}{K_т \cdot K_y} = 112.5$$

Natural frequency of the current loop:

$$\omega_T := \frac{1}{\sqrt{2} T_y} = 1.768 \times 10^3 \quad c^{-1}$$

Transfer function of the current controller:

$$П_{рто}(s) := \frac{1 + \tau_{рт} \cdot s}{s} \rightarrow \frac{0.008 \cdot s + 1}{s}$$

A polynomial that takes into account the inertial properties of the converter and the electric circuit of the motor:

$$B(s) := (1 + T_y \cdot s)(1 + T_э \cdot s)$$

Current open loop transfer function:

$$П_T(s) := r_T \cdot \frac{П_{рто}(s)}{B(s)} \rightarrow \frac{1250}{s \cdot (0.0004 \cdot s + 1)}$$

Total current loop gain (min , max , avg):

$$r_{min} := r_T \cdot T_{м_мин} = 3.198$$

$$r_{max} := r_T \cdot T_{м_макс} = 4.51$$

$$r := r_T \cdot T_{м_ср} = 3.854$$

speed loop. Let's choose a PI controller as a speed loop controller.

Speed open loop transfer function:

$$W_c(s) = \frac{\nu \cdot (1 + \tau_{pm} \cdot s) \cdot (1 + \tau_{pc} \cdot s)}{s^2 \cdot ((1 + T_y \cdot s) \cdot (1 + T_m \cdot s + T_m \cdot T_э \cdot s^2) + r \cdot (1 + T_э \cdot s))}$$

Simplified approximation of the speed open-loop transfer function:

$$W_c(s) = \frac{\nu \cdot (1 + \tau_{pc} \cdot s)}{(1 + r) \cdot s^2 \cdot \left(1 + \frac{T_m}{1 + r} \cdot s\right)}$$

Given that:

$$\frac{T_m}{1 + r} = \frac{T_m}{1 + r_1 \cdot T_m} = \frac{1}{\frac{1}{T_m} + \frac{1}{2 \cdot T_y}} = 2 \cdot T_y$$

We obtain a simplified transfer function of the velocity loop:

$$W_c(s)=\frac{\nu\cdot(1+\tau_{pc}\cdot s)}{(1+r)\cdot s^2\cdot(1+2\cdot T_y\cdot s)}$$

For the speed loop with second-order astatism in terms of the control action, the standard setting of CO is known. The parameters are chosen in such a way that the following relationship is provided:

$\omega_2 := \frac{1}{2\cdot T_y} = 1.25\times 10^3$ c^{-1}

$\frac{\omega_2}{\omega_{сск_макс}} = \frac{1}{2}$, тогда $\omega_{сск_макс} := \frac{\omega_2}{2} = 625$ c^{-1}

$f_{сск_макс} := \frac{\omega_{сск_макс}}{2\cdot\pi} = 99.472$ Гц

Gain Ratio:

$d := \frac{1+r_{max}}{1+r_{min}} = 1.313$ $20\cdot\log(d) = 2.362$ дБ

Cutoff frequency limits:

$\omega_{сск_мин} := \frac{\omega_{сск_макс}}{d} = 476.181$ c^{-1}

$f_{сск_мин} := \frac{\omega_{сск_мин}}{2\cdot\pi} = 75.787$ Гц

$\omega_{сск_ср} := \omega_{сск_макс}\cdot\frac{1+r_{min}}{1+r} = 540.534$ c^{-1}

$f_{сск_ср} := \frac{\omega_{сск_ср}}{2\cdot\pi} = 86.029$ Гц > 70 Гц, подходит

Учитывая условие $M_{ск} < 2$, приму $M_{ск} := 1.9$

$\frac{M_{ск}}{M_{ск}-1}\cdot\frac{1+r_{max}}{1+r_{min}} = \frac{\omega_{с.ск_max}}{\omega_{рс}}$, тогда:

$\tau_{рс} := \frac{M_{ск}}{M_{ск}-1}\cdot\frac{1+r_{max}}{1+r_{min}}\cdot 4T_y = 4.433\times 10^{-3}$

Speed loop natural frequency:

$$\omega_{pc} := \frac{1}{\tau_{pc}} = 225.559 \quad c^{-1}$$

$$\frac{M_{ск}}{M_{ск}-1}\cdot\frac{1+r_{max}}{1+r_{min}} = \frac{\nu}{(1+r_{min})\omega_1^{\,2}}$$

Overall speed loop gain:

$$\nu := \frac{M_{ск}}{M_{ск}-1}\cdot(1+r_{max})\cdot\omega_{pc}^{\,2} = 5.918\times 10^{5}$$

Construction of the boundary LAFC of the velocity contour:

$$\omega := 1, 2 .. 1500 \qquad I := -50, 0 .. 50 \qquad s(\omega) := i\omega$$

$$W_{c_макс}(\omega) := \frac{\nu\cdot(1+\tau_{pc}\cdot s(\omega))}{(1+r_{min})\cdot s(\omega)^2\cdot(1+2\cdot T_y\cdot s(\omega))} \qquad L_{c_макс}(\omega) := 20\cdot\log(|W_{c_макс}(\omega)|)$$

$$W_{c_мин}(\omega) := \frac{\nu\cdot(1+\tau_{pc}\cdot s(\omega))}{(1+r_{max})\cdot s(\omega)^2\cdot(1+2\cdot T_y\cdot s(\omega))} \qquad L_{c_мин}(\omega) := 20\cdot\log(|W_{c_мин}(\omega)|)$$

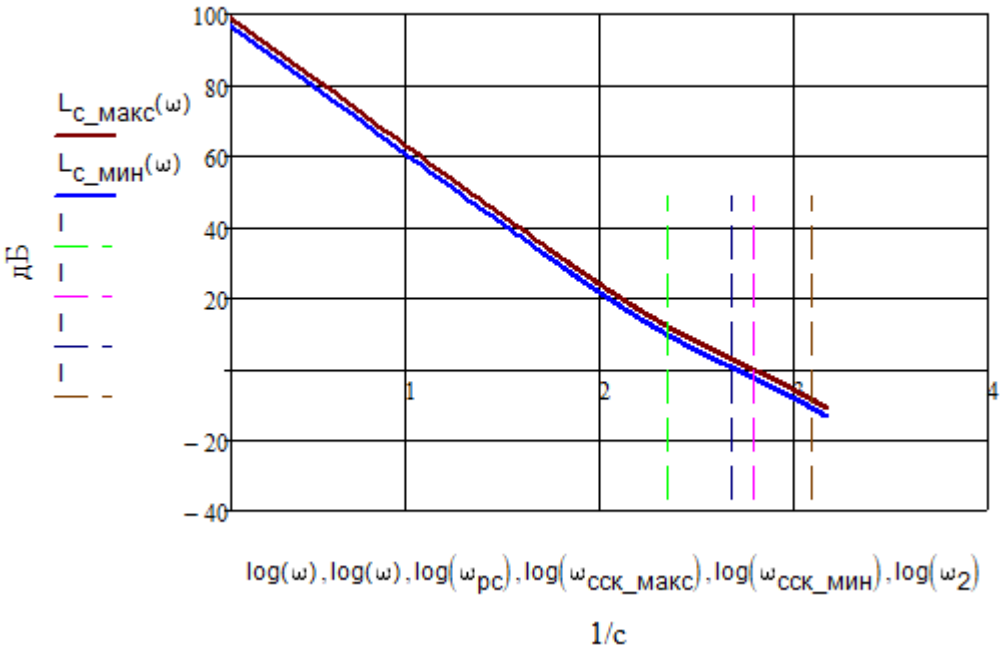


Figure 8 - LAFC of the speed loop

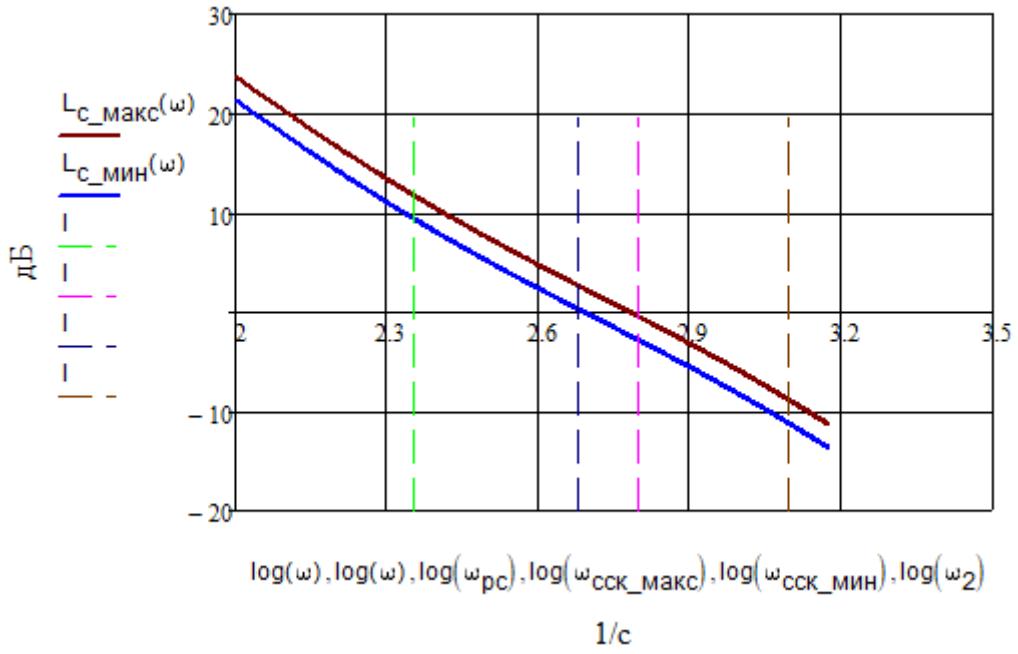


Figure 9 - LAFC of the speed loop

Verification calculation of the speed loop for the average value of the moment of inertia of the load:

The calculation technique consists in presenting the inverse transfer function of an open loop of speed as the sum of two terms - in this case, if we divide the second term by the first, we get the transfer function of an open current loop. The difference in the logarithmic scale of the LAFC of the first and second terms must coincide with the LAFC of the transfer function of an open current loop. Calculations are carried out on the average value of the moment of inertia of the load.

$$W_c^{-1}(s) = \frac{A(s)}{\nu \cdot \Pi_{pc0}(s) \cdot \Pi_{pt0}(s)} + \frac{r}{\nu} \cdot \frac{s}{\Pi_{pc0}(s)} = \frac{s^2 \cdot (1 + T_y \cdot s) \cdot \left(1 + T_{м_ср} \cdot s + T_{м_ср} \cdot T_э \cdot s^2\right)}{\Pi_{pco}(s) \cdot \Pi_{pto}(s) \nu} +$$

$$+ \frac{r}{\nu} \cdot \frac{s^2}{\Pi_{pco}(s)}$$

$K_{pc} := \frac{\nu \cdot K_w}{K_c \cdot K_{pt} \cdot K_y} = 515.519$ - коэффициент усиления регулятора тока

$\Pi_{pco}(s) := \frac{(1 + \tau_{pc} \cdot s)}{s}$

$\Pi_{pc}(s) := K_{pc} \cdot \Pi_{pco}(s)\ \text{float}, 3 \rightarrow \frac{516.0 \cdot (0.00443 \cdot s + 1.0)}{s}$ -передаточная функция ПИ-регулятора контура скорости

$W_1(\omega) := \frac{(1 + T_y \cdot s(\omega)) \cdot \left(1 + T_{м_ср} \cdot s(\omega) + T_{м_ср} \cdot T_э \cdot s(\omega)^2\right)}{\Pi_{pco}(s(\omega)) \cdot \Pi_{pto}(s(\omega)) \nu}$ $L_1(\omega) := 20 \log\left(\left|W_1(\omega)\right|\right)$

$W_2(\omega) := \frac{r}{\nu} \cdot \frac{s(\omega)}{\Pi_{pco}(s(\omega))}$ $L_2(\omega) := 20 \log\left(\left|W_2(\omega)\right|\right)$

$L(\omega) := L_2(\omega) - L_1(\omega)$

$W_T(s) = r_{ср} \cdot \frac{s \cdot \Pi_{pm0}(s)}{A(s)}$ - передаточная функция разомкнутого контура тока

$W_T(\omega) := r \cdot \frac{s(\omega) \cdot \Pi_{pto}(s(\omega))}{\left(1 + T_{м_ср} \cdot s(\omega) + T_{м_ср} \cdot T_э \cdot s(\omega)^2\right) \cdot (1 + T_y \cdot s(\omega))}$

$L_T(\omega) := 20 \cdot \log\left(\left|W_T(\omega)\right|\right)$

$\omega_м := \frac{1}{T_{м_ср}} = 324.35 \quad c^{-1}$ $\omega_y := \frac{1}{T_y} = 2.5 \times 10^3 \quad c^{-1}$ $\omega_{pt} := \frac{1}{\tau_{pt}} = 125 \quad c^{-1}$

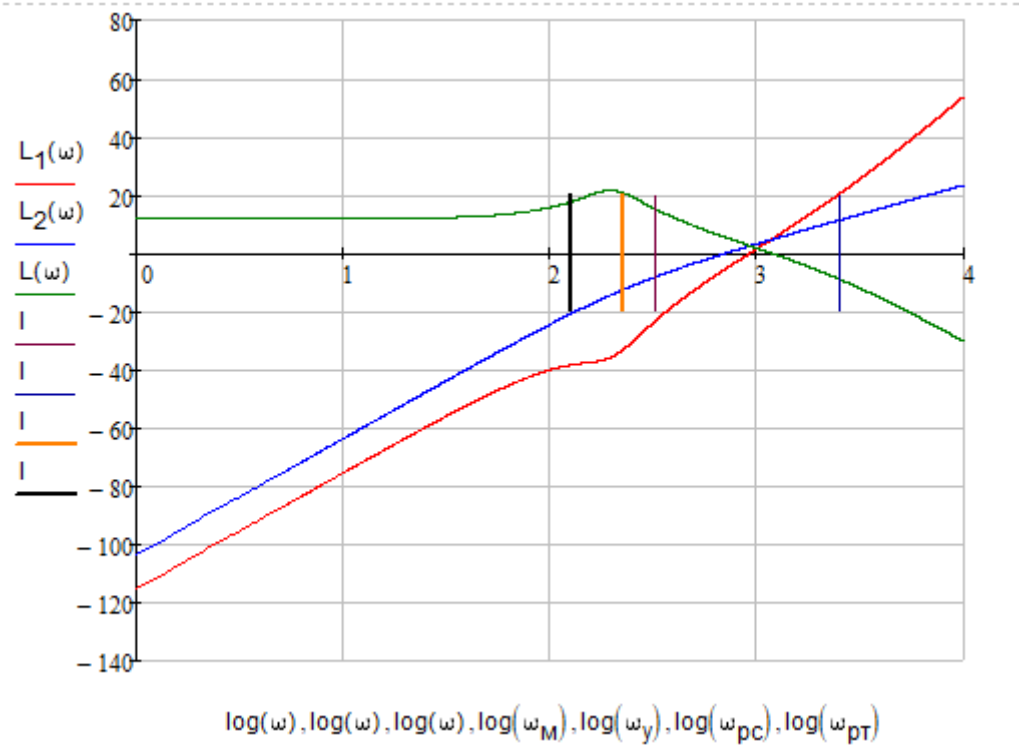


Figure 10 - Speed loop

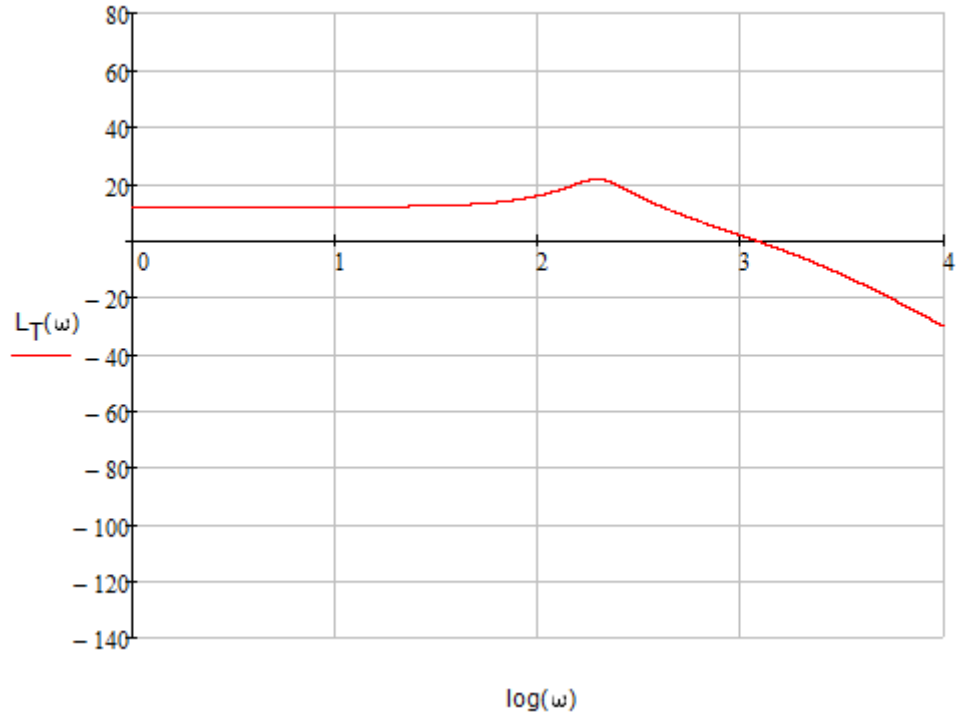


Figure 11 - LAFC of the open transfer function of the current loop.

Thus, from the constructed LAFC, we can conclude that the ratio of the second term of the inverse transfer function of an open loop of speed to the first one coincides

with the LAFC of the transfer function of an open current loop. Therefore the speed loop calculation is correct.

Position contour. The position open-loop transfer function is:

$$W_n(s)=\frac{\mu\cdot\Pi_{pn0}(s)\cdot\Pi_{pc0}(s)\cdot\Pi_{pm0}(s)}{s\left(A(s)+\nu\cdot\Pi_{pc0}(s)\cdot\Pi_{pm0}(s)+r\cdot s\cdot\Pi_{pm0}(s)\right)}$$

and the inverse transfer function:

$$W_n^{-1}(s)=\frac{s\cdot A(s)}{\mu\cdot\Pi_{pn0}(s)\cdot\Pi_{pc0}(s)\cdot\Pi_{pm0}(s)}+\frac{\nu\cdot s}{\mu\cdot\Pi_{pn0}(s)}+\frac{r\cdot s^2}{\mu\cdot\Pi_{pn0}(s)\cdot\Pi_{pc0}(s)}$$

$$|W_{II}(j\omega)|>>|W_I(j\omega)+W_{III}(j\omega)| \quad \text{, так как} \quad \frac{\nu}{\mu}>>\frac{1}{\mu},\ \frac{\nu}{\mu}>>\frac{r}{\mu}$$

The contour parameters determine the second term of the inverse transfer function:

$$W_n(s)=\frac{\mu\cdot\Pi_{pn0}(s)}{\nu\cdot s}$$

We will set the desired LFC in the low and medium frequencies

Working point parameters:

$$\omega_p := \frac{a_{max}}{} = 1.25 \quad c^{-1}$$

$$K_p := \frac{\omega_{max}^{2}}{a_{max}\cdot E_{max}} = 128$$

Oscillation index (requirement for the quality of the transient process):

$M_п < 1.3$, выберем $M_п := 1.2$

$$d := 20\cdot\log\left(\frac{M_п}{M_п-1}\right) = 15.563 \quad дБ$$

Maximum cutoff frequency (performance requirements):

$$\omega_{сп_макс} := \frac{\omega_{сск_мин}}{3} = 158.727 \quad c^{-1}$$

Draw the asymptote BC through the operating point with a slope of -20 dB/dec. In this case, the cutoff frequency is greater than the maximum possible, which can lead to system instability. If the asymptote of AG is plotted with a slope of -40dB/dec, then the BAG line and frequencies above the maximum cutoff frequency form a forbidden region.

$$f_1(\omega) := 20 \cdot \log(K_p) - 20 \cdot \log(\omega) + 20 \cdot \log(\omega_p)$$

$$f_2(\omega) := 20 \cdot \log(K_p) - 40 \cdot \log(\omega) + 40 \cdot \log(\omega_p)$$

To plot the desired LAFR, draw the asymptote DE with a slope of -40dB/dek 3dB above the operating point Ap to meet the accuracy requirements.

Point E is obtained according to the requirements for the quality of the transient process.

$$DE(\omega) := 20 \cdot \log(K_p) + 3 - 40 \cdot \log(\omega) + 40 \cdot \log(\omega_p)$$

$$\omega_E := 5$$

$$\omega_E := \text{root}(DE(\omega_E) - d, \omega_E) = 6.862 \quad c^{-1} \qquad \omega_{DE} := 1, 2 .. \omega_E$$

Next, we draw the EF asymptote with a slope of -20dB/dec. In this case, the cutoff frequency will be less than the maximum, which will ensure speed and maintain the stability of the system. The DEF line forms the desired position open-loop LAFC.

$$EF(\omega) := d - 20 \cdot \log(\omega) + 20 \cdot \log(\omega_E) \qquad \omega_{EF} := \omega_E, \omega_E + 1 .. 250$$

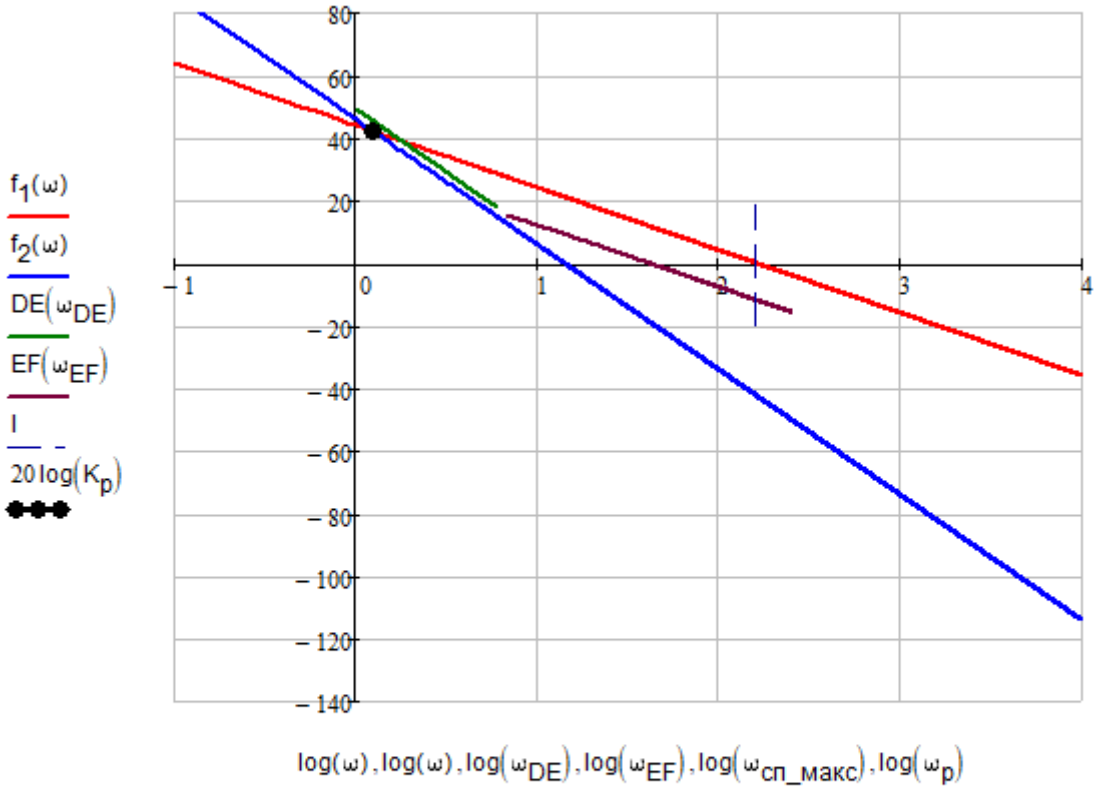


Figure 12 - LAFC of the open position loop.

According to the desired LAFC, we determine the following parameters:

$A := DE(1) = 49.02$ дБ $\qquad \omega_1 := \omega_E = 6.862 \quad c^{-1}$

$\omega_{сп} := 30 \qquad \omega_{сп} := root(EF(\omega_{сп}), \omega_{сп}) = 41.171 \quad c^{-1}$

Contour options:

$M_п := \frac{\omega_{сп}}{\omega_{сп} - \omega_1} = 1.2$ - требование выполненно

$\tau_{рп} := \frac{1}{\omega_1} = 0.146$ с - постоянная времени регулятора положения

$K := 10^{\frac{A}{20}} = 282.508 \qquad \mu := K \cdot \nu = 1.672 \times 10^8$

Desired transfer function:

$$W_n(s)=\frac{\mu \cdot \Pi_{pn0}(s)}{\nu \cdot s}$$

$$W_П(s) := K\cdot\frac{1+\tau_{pп}\cdot s}{s^2}\ \text{float}\ ,3\ \rightarrow \frac{283.0\cdot(0.146\cdot s+1.0)}{s^2}$$

The desired function will be provided by the PI controller

$$\Pi_{pn}(s)=K_{pn}\cdot\frac{1+\tau_{pn}\cdot s}{s}$$

$$K_{pп} := \frac{\mu\cdot K_W\cdot I}{K_y\cdot K_{pc}\cdot K_{pт}} = 7.402\times 10^4$$

Verification calculation of the position contour. The calculation technique is to represent the inverse transfer function of an open loop as the sum of three terms - in this case, if you divide the sum of the first and third terms by the second, you get the inverse transfer function of an open loop of speed. The cutoff frequencies for current and speed will allow us to conclude that the calculation is correct. Calculations are carried out on the average value of the moment of inertia of the load.

$$W_П^{-1}(s) = \frac{s\cdot A(s)}{\mu\,\Pi_{pco}(s)\cdot\Pi_{pп0}(s)\cdot\Pi_{pт0}(s)} + \frac{\nu}{\mu}\cdot\frac{s}{\Pi_{pп0}(s)} + \frac{r}{\mu}\cdot\frac{s^2}{\Pi_{pп0}(s)\,\Pi_{pc0}(s)}$$

$$\omega := 0\ ,0.2\ ..\ 10000$$

$$s(\omega) := i\omega$$

$$W_1(\omega) := \frac{\left(1+T_y\cdot s(\omega)\right)\cdot\left(1+T_{M_cp}\cdot s(\omega)\right)\cdot\left(1+T_э\cdot s(\omega)\right)\cdot s(\omega)^4}{\mu\cdot\left(1+\tau_{pc}\cdot s(\omega)\right)\cdot\left(1+\tau_{pп}\cdot s(\omega)\right)\cdot\left(1+\tau_{pт}\cdot s(\omega)\right)} \qquad L_1(\omega) := 20\log\left(\left|W_1(\omega)\right|\right)$$

$$W_2(\omega) := \frac{\nu}{\mu}\cdot\frac{s(\omega)^2}{\left(1+\tau_{pп}\cdot s(\omega)\right)} \qquad L_2(\omega) := 20\log\left(\left|W_2(\omega)\right|\right)$$

$$W_3(\omega) := \frac{r}{\mu}\cdot\frac{s(\omega)^4}{\left(1+\tau_{pc}\cdot s(\omega)\right)\cdot\left(1+\tau_{pп}\cdot s(\omega)\right)} \qquad L_3(\omega) := 20\log\left(\left|W_3(\omega)\right|\right)$$

$$L(\omega) := 20\cdot\log\left(\left|W_3(\omega)+W_1(\omega)\right|\right) - L_2(\omega)$$

Inverse transfer function of the speed loop:

$$W_c(\omega) := \frac{(1 + T_y \cdot s(\omega)) \cdot (1 + T_{M_cp} \cdot s(\omega)) \cdot (1 + T_э \cdot s(\omega)) \cdot s(\omega)^2}{\nu \cdot (1 + \tau_{pc} \cdot s(\omega)) \cdot (1 + \tau_{pT} \cdot s(\omega))} + \frac{r}{\nu} \frac{s(\omega)^2}{1 + \tau_{pc} \cdot s(\omega)}$$

$$L_c(\omega) := 20 \cdot \log(|W_c(\omega)|) \qquad \omega := 1, 1.1 .. 10000$$

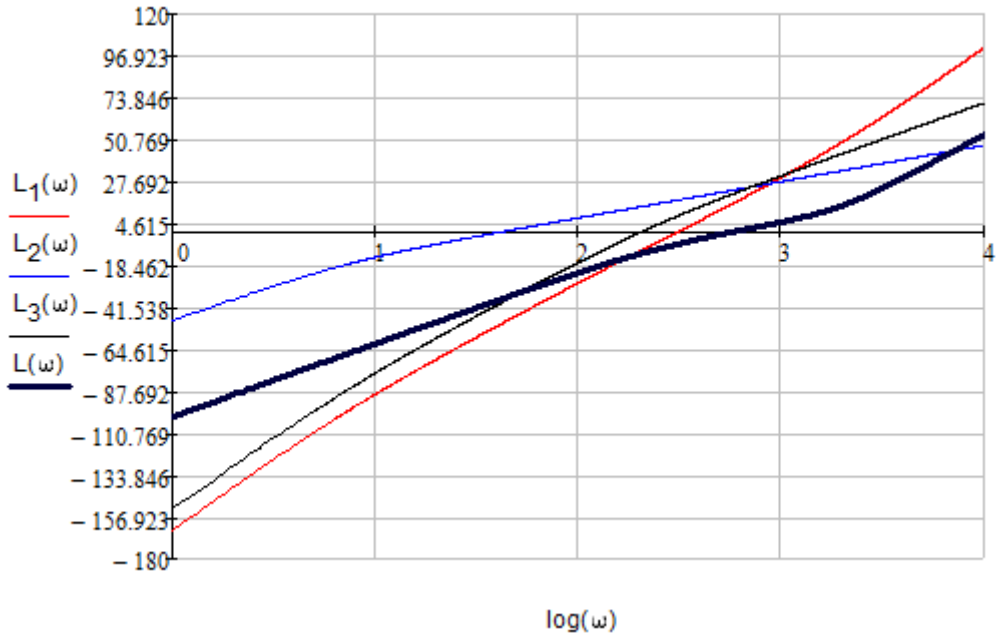


Figure 13 - Speed loop

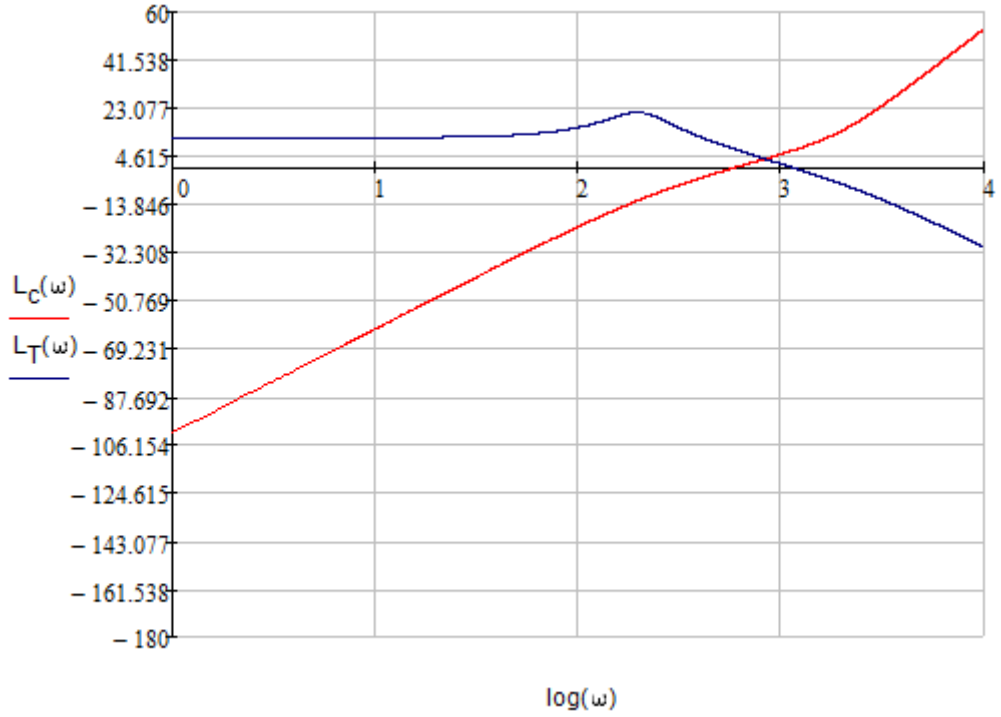


Figure 14 - LACH

It can be seen that the LAFC of the ratio of the sum of the first and third terms of the inverse transfer function of the open position loop to the second one coincides with the LAFC of the inverse transfer function of the open velocity loop, which means that everything is done correctly. It can also be seen that the cutoff frequency of the speed loop is less than the cutoff frequency of the current loop, which indicates the stability of the system.

Thus, the types were determined and the parameters of the current, speed and position controllers were selected:

$K_{рт} = 112.5$ $K_{рс} = 515.519$ $K_{рп} = 7.402 \times 10^4$

$\tau_{рт} \rightarrow 0.008$ $\tau_{рс}$ float , 3 $\rightarrow 0.00443$ $\tau_{рп} = 0.146$

1.5.3. Modeling the developed system

Let's model the system in the Matlab environment, the Simulink package. A stepped signal will be applied to the input of each of the circuits. Also, to check the stability, LFC and PFC of each of the circuits will be built.

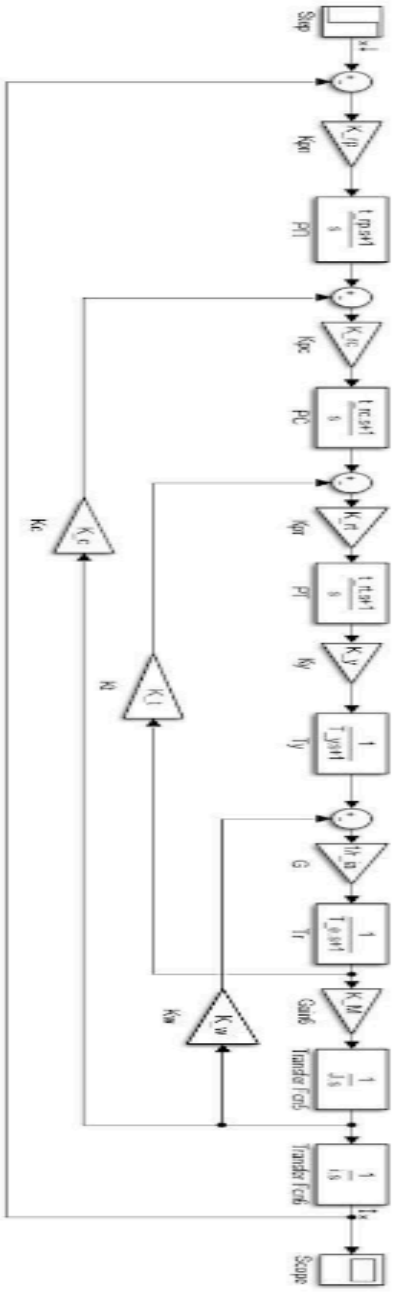


Figure 4 - Structural diagram of the servo drive for turning the camera

Position loop analysis. Loop response of the position contour:

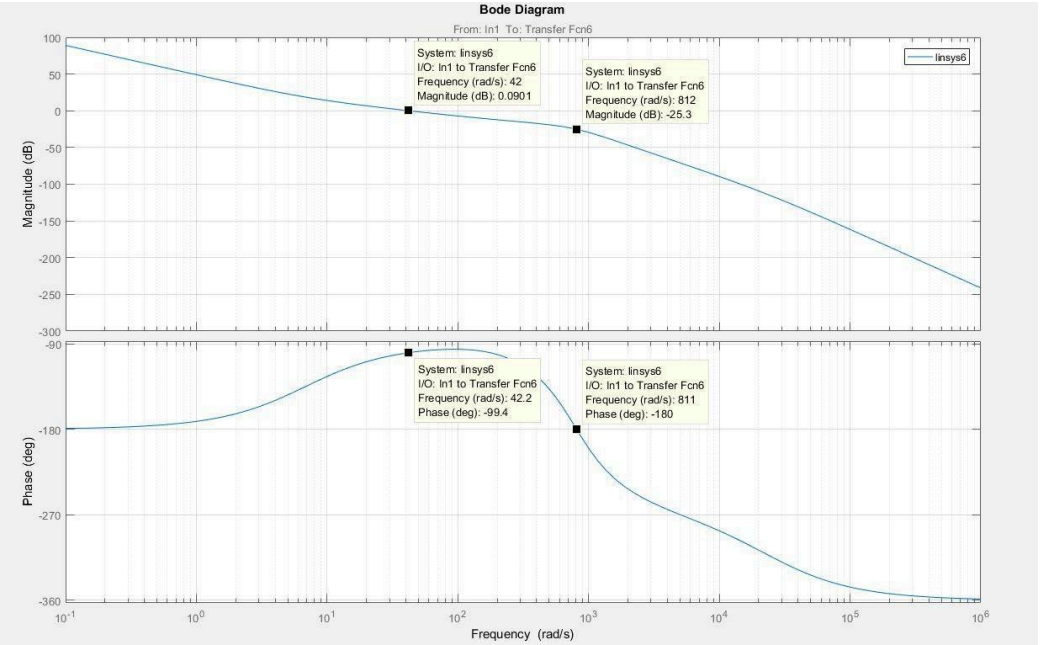


Figure 5 - LPFC of the position contour

The cutoff frequency of the position loop is 42 rad/s. It is less than the frequency of the corresponding phase -180˚, which means the system is stable.

Amplitude margin : ΔA = 25.3 Phase margin Δφ= 80.6 ˚ Position loop step response:

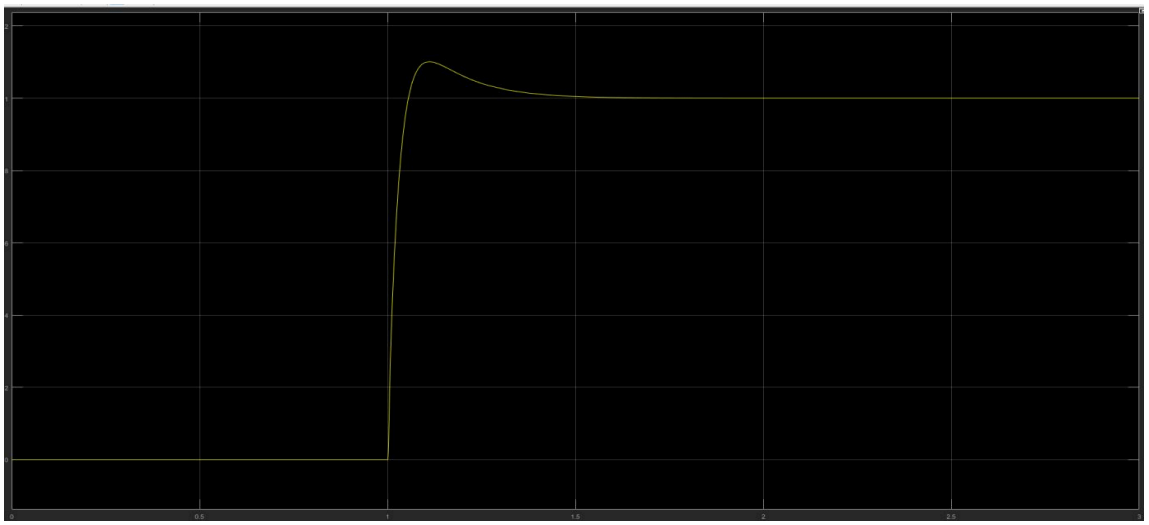


Figure 6 - Response to the step action of the position loop. The overshoot is less than 10%.

Velocity loop analysis. LFFC of the speed loop:

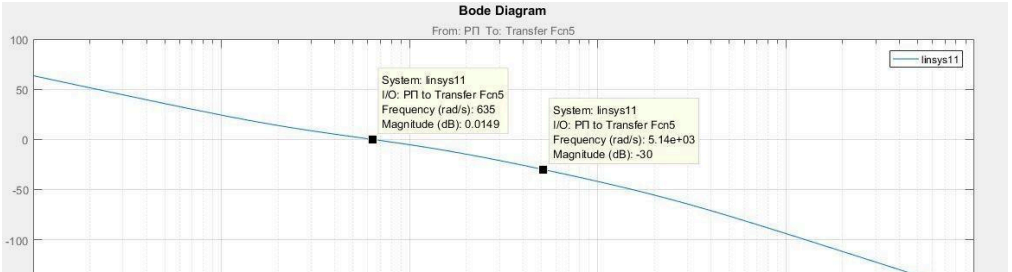


Figure 7 - LPFC of the speed loop

The cutoff frequency of the position loop is 635 rad/s. It is less than the frequency of the corresponding phase -180˚, which means the system is stable. Amplitude stability margin: ΔA = 30 Phase stability margin Δφ= 43˚

Transient response of the speed loop:

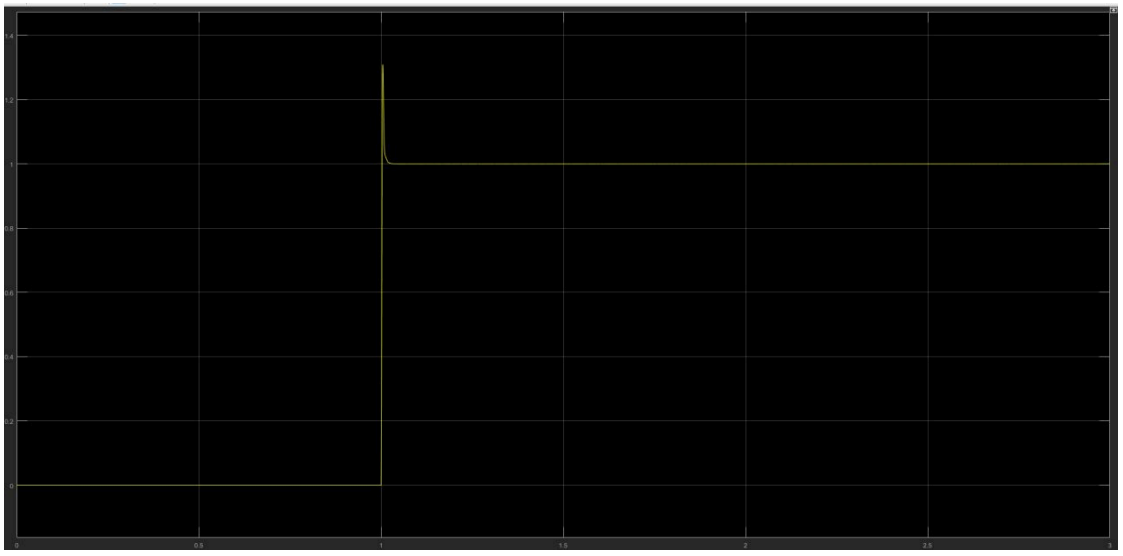


Figure 8 - Response to the step action of the speed loop Overshoot was 30%.

Current loop analysis. LFFC of the current circuit:

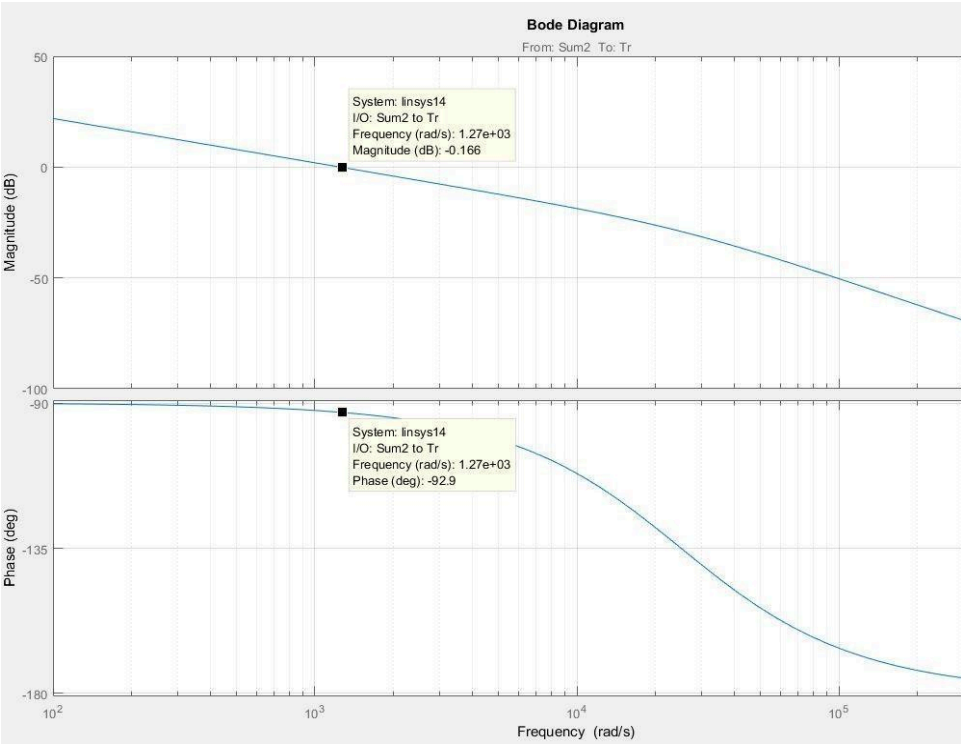


Figure 9 - LPFC of the current circuit

The cutoff frequency of the position loop is 1270 rad/s. It is less than the frequency of the corresponding phase -180˚, which means the system is stable. Phase stability margin Δφ= 87.1˚. Step response of the position loop:

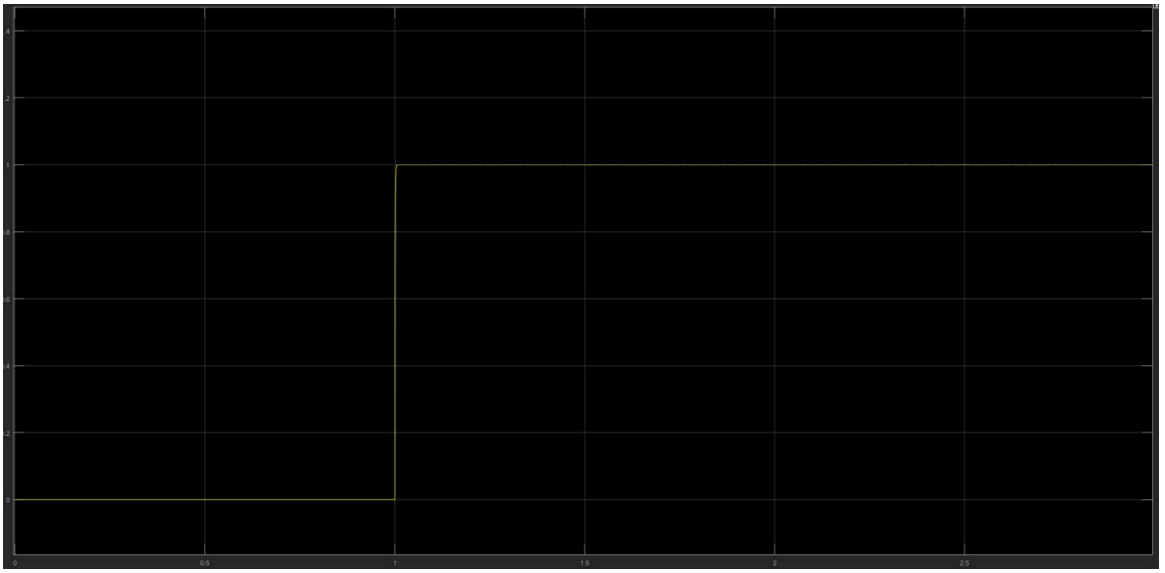


Figure 10 - Response to the stepped action of the current loop

Thus, the contours of the current, speed and position of the servo drive were investigated

1.6 Computer Vision system

1.6.1 Vision system module

This paragraph describes the development of a VS for a parking inspector robot. The function that it performs is to determine the number of the car. According to GOST 50577-93, car license plates have a standardized look (Figure 11).



Figure 11 - License plate of the car

To solve this problem, we use the following algorithm:

1. Determining the license plate on a vehicle
2. Extracting a number from an image
3. Segmentation of each of the characters of the number
4. Symbol classification

At present, the field of technical vision is increasingly occupied by convolutional neural networks, which give a significant advantage of such systems is the higher resistance of the system to changes in the environment: the number may be dirty, a different color, the shooting angle may change, etc. Analyzing the advantages of neural networks, a decision was made and the application of neural network algorithms of STZ. Thus, the task is reduced to determining the architecture of networks.

1.6.2. Vehicle license plate identification

The system input is a photograph of the vehicle itself. The first thing to do is determine the position of the number on the machine. For this task, we will use an architecture called Faster R-CNN (Figure 12)

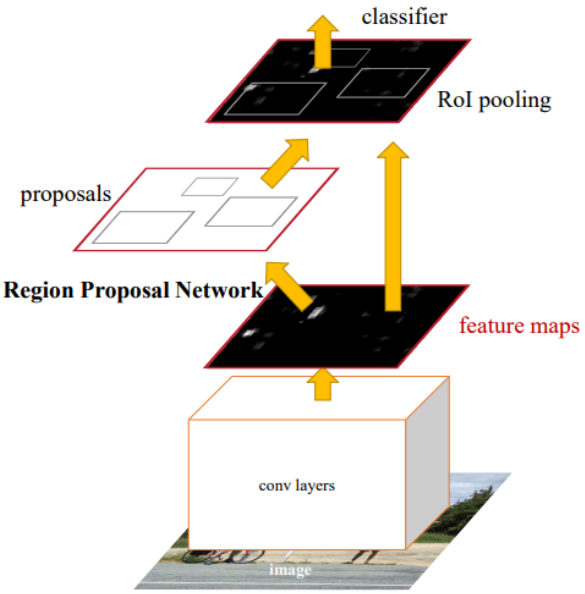


Figure 12 - Faster R-CNN

The algorithm for detecting an object using this solution consists of two stages: determining the zones in which the object can theoretically be located and classifying the object in a certain zone.

1.6.3 Determination of object zones on the camera

First of all, the so-called feature map is obtained from the image. To do this, the image needs to go through convolutional layers.

$$y[m,\ n] = x[m,n] * h[m,n] = \sum_{j=-\infty}^{\infty} \sum_{i=-\infty}^{\infty} x[i,\ j] * h[m - i,\ n - j]$$

Here x is the convolution kernel;

h is the matrix of the original image;

$m,\ n$ - vertical and horizontal dimensions of the image, respectively;

i - vertical coordinate of a pixel;

j - horizontal pixel coordinate;

The architecture of convolutional layers is presented in Table 1.

Table 1 - Convolutional layers of the network

layer type	Kernel size
Convolutional	120x5x5
Maximum	120x4x4
Convolutional	384x2x2
Maximum	384x2x2

A feature map is a “convenient” interpretation of an image for a computer system with selected features of interest. This approach ensures the correct preparation of data for the subsequent neural network.

As mentioned earlier, the first step is to segment the image. At this stage, a fully connected neural network is used (Fig. 13), with 256 neurons in the hidden layer and two output layers, 2k *and* 4k *neurons* in size. Here *k* is the number of types of framing zones in which the object can theoretically be located.

The first layer predicts what type of zone the object lies in, and the second determines the coordinates of the center of this zone.

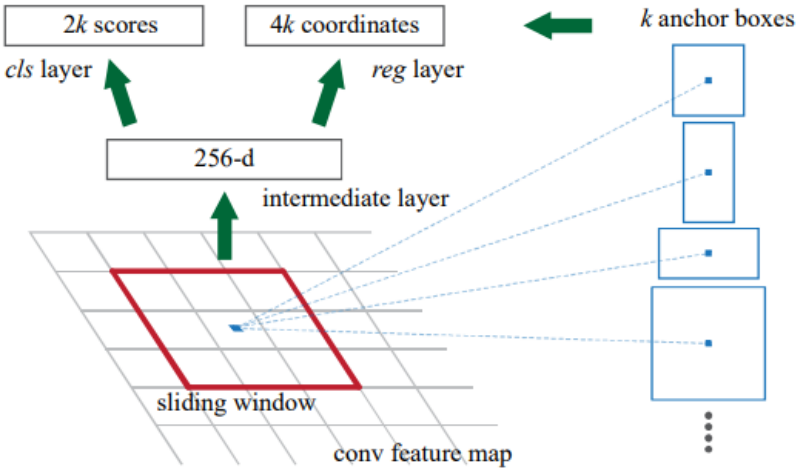


Figure 13 - The stage of determining the framing zones

In the course of the work, it was found that the maximum accuracy with minimal computational costs is obtained at $n = 3$ and $k = 3$.

The activation function of neurons in the hidden layer is Relu (Figure 14.):

$$Relu = max(0, x)$$

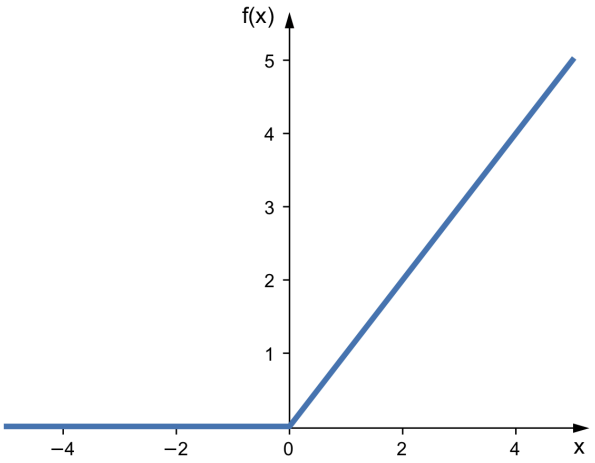


Figure 14 - Relu neuron activation function

The activation function of neurons in the output layer is softmax:

$$\sigma(z)_i = \frac{e^{z_i}}{\sum_{k=1}^{K} e^{z_k}}$$

Here z_i- i -th example for the network;

The cross entropy is used as the loss function.

$$CE = -\sum_{i}^{C} t_i log(f(a)_i)$$

Here a_i, is the value predicted by the network for *the i* -th example;

t_i- i -th actual value;

One of the most successful neural network training optimization methods is DropOut. Its essence lies in the fact that each neuron can be excluded for one iteration with a certain probability p. Thus, the activation function of this neuron changes:

$$f(h) = D \odot a(h)$$

Where is $D = \{X_1 \dots X_n\}$a vector indicating whether the corresponding neuron will be excluded from the network. Let us denote the activation function of the neuron differently:

$$O_i = X_i a(\sum_{k=1}^{d_i} w_k x_k + b) = \begin{cases} a(\sum_{k=1}^{d_i} w_k x_k + b), & \text{если } X_i = 1, \\ 0, & \text{если } X_i = 0 \end{cases}$$

During the experiments, the probability values *p*were taken equal to 0.5.

1.6.4. Classification of an object in an image

To classify an object in the zone, a fully connected neural network with 384 neurons on the first hidden layer, 64 on the second, and one output neuron was chosen. This choice was made from the conditions of the fastest learning ability of

the network. Figure 15 shows comparative values for different network architectures (with different numbers of layers and neurons).

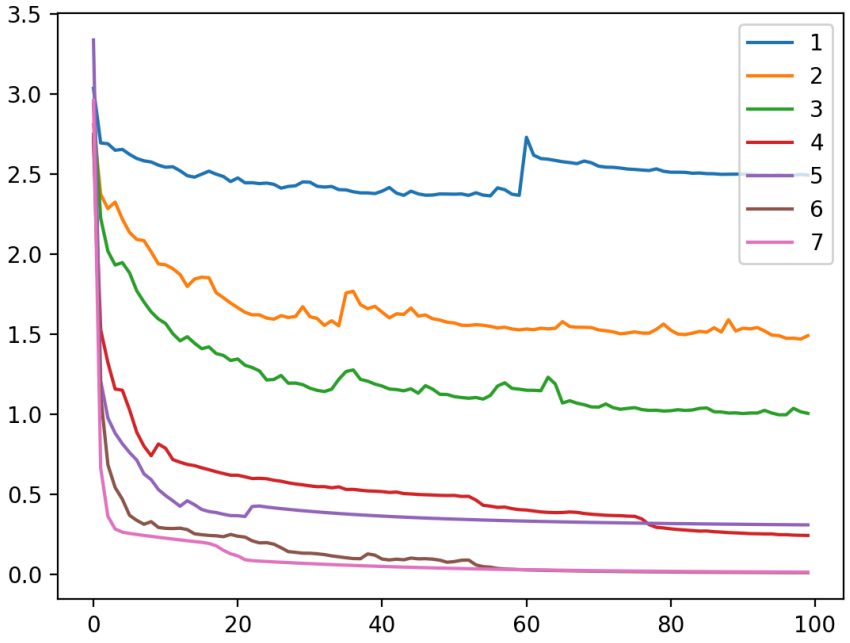


Figure 15 - Training schedule for various types of neural networks

As in the case of a neural network to determine the framing zones, Relu is used as the activation function of the hidden layers,

$$Relu = max(0, x)$$

and weekends - softmax.

$$\sigma(z)_i = \frac{e^{z_i}}{\sum_{k=1}^{K} e^{z_k}}$$

There was also cross-entropy as a loss function.

$$CE = -\sum_{i}^{C} t_i log(f(s)_i)$$

As an input to the neural network, a vector is supplied, the dimension of which is equal to the dimensions of the map with a sign (in our case 384x1) the product of the width and height of which is equal to the length of the vector. The result of the network is the probability of finding an object in a certain zone. Table 2 shows the final architecture of the neural network for finding the license plate of a car.

Table 2 - Final network architecture

layer type	Core (layer) size
Convolutional	120x5x5
Maximum	120x4x4
Convolutional	384x2x2
Maximum	384x2x2
Fully Connected	384
Fully Connected	64
Fully Connected	13

1.6.5. Image segmentation

When we know the position of the number, we can cut it out and apply it to the next modules of the system. The next step is to segment the image to find the characters directly on the license plate. The algorithm used in this work is called MeanShift. This method groups objects with similar features. Pixels with similar features are combined into one segment, at the output we get an image with homogeneous areas.

Let us introduce the point density function:

$$f(\underline{x}^{>}) = \frac{1}{Nh^{d}} \sum_{i=1}^{N} K(\frac{\underline{x}^{>} - \underline{x}_{i}^{>}}{h})$$

$\underline{x}_{i}^{>}$is the feature vector of $i$the th pixel, $d$is the number of features, $N$is the number of pixels, $h$is the parameter responsible for smoothness, $K(\underline{x}^{>})$is the kernel. The maxima of the function $f(\underline{x}^{>})$are located at the points of condensation of image pixels in the feature space. Pixels belonging to the same local maximum are combined into one segment. It turns out that in order to find which of the centers of condensation a pixel belongs to, one must step along the gradient $f(\underline{x}^{>})$to find the nearest local maximum.

To estimate the gradient of the density function, you can use the mean shift vector$M_{h}(\underline{x}^{>})$

as the kernel $K(\underline{x}^{>})$:

$$K_{E}(\underline{x}^{>}) = \begin{cases} \frac{1}{2c_{d}}(d+2)(1-\underline{x}^{>T}\underline{x}^{>}), \text{если } \underline{x}^{>T}\underline{x}^{>} < 1 \\ 0, \quad \text{в остальных случаях} \end{cases}$$

$c_d$is the volume of a d-dimensional sphere with unit radius.

$$grad(f(\underline{x}^{>})) = \frac{1}{Nh^d}\sum_{i=1}^{N} grad\left(K\left(\frac{\underline{x}^{>}-\underline{x}^{>}_i}{h}\right)\right) = \frac{1}{N(h^d c_d)}\frac{d+2}{h^2}\sum_{\underline{x}^{>}_i \in S_h(\underline{x}^{>})}(\underline{x}^{>}_i - \underline{x}^{>}) =$$

$$= \frac{n_{h,\underline{x}^{>}}}{N(h^d c_d)}\frac{d+2}{h^2}\left(\frac{1}{n_{h,\underline{x}^{>}}}\sum_{\underline{x}^{>}_i \in S_h(\underline{x}^{>})}\left(\underline{x}^{>}_i - \underline{x}^{>}\right)\right)$$

$\underline{x}^{>}_i \in S_h(\underline{x}^{>})$means that the sum does not go over all pixels, but only over those that fall into a sphere $h$with a radius centered at the point where the vector points $\underline{x}^{>}$in the feature space. This is introduced on purpose to reduce the number of calculations. $(h^d c_d)$— the volume of da -dimensional sphere $c$with a radius h, You can separately set the radius for spatial coordinates and separately the radius in the space of colors. $n_{h,\underline{x}^{>}}$is the number of pixels in the sphere. A quantity $\frac{n_{h,\underline{x}^{>}}}{N(h^d c_d)}$can be thought of as an estimate of the value $f(\underline{x}^{>})$in the area $S_h(\underline{x}^{>})$.

$$M_h(\underline{x}^{>}) = \frac{1}{n_{h,\underline{x}^{>}}}\sum_{\underline{x}^{>}_i \in S_h(\underline{x}^{>})}\left(\underline{x}^{>}_i - \underline{x}^{>}\right)$$

$$grad(f(\underline{x}^{>})) = f(\underline{x}^{>})\frac{d+2}{h^2}M_h(\underline{x}^{>})$$

Therefore, to walk along the gradient, it is enough to calculate the value $M_h(\underline{x}^{>})$- the average shift vector. It should be remembered that when choosing a different kernel, the mean shift vector will look different.

When choosing pixel coordinates and color intensities as features, pixels with similar colors and located close to each other will be combined into one segment.

Accordingly, if you choose another feature vector, then the combination of pixels into segments will already follow it.

The results of the algorithm are shown in Figure 16:

A)



b)

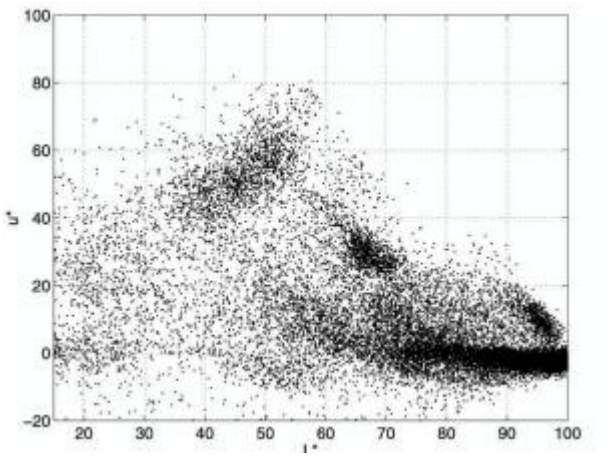


Figure 16 - MeanShift results. a) The result of the algorithm; b) Pixels in 2D Feature Space

Thus, this algorithm successfully displayed the image necessary for further processing, in other words, grouped objects with similar features. Pixels with similar features are combined into one segment, resulting in an image with homogeneous areas.

Advantages of the algorithm:

1. The algorithm is application and environment independent means that is suitable for real data.

2. The algorithm is capable of processing arbitrary spaces of required features.
3. There is no need to pre-size the clusters.

Flaws:

1. It is often necessary to use self-setting window size.
2. The choice of window size is not trivial.

Recognition of signs on the license plate. Sign recognition in this system occurs in two stages:

1. Image segmentation
2. Recognizing each of the characters using a convolutional neural network

License plate segmentation has already been implemented, which means that it remains only to decide on the architecture of the neural network for recognizing signs in the image.

Each symbol of the sign is fed into the network input separately, but, nevertheless, it is necessary to train exactly one convolutional neural network in order to optimize the work.

During the simulation of the system operation, several types of convolutional neural networks with different architectures were used. The best quality of work was shown by the network, the architecture of which is presented in Table 3.

Table 3 - Architecture of the network for recognizing signs on a license plate

layer type	Kernel size
Convolutional	64x3x3

Maximum	64x3x3
Convolutional	128x3x3
Maximum	128x3x3
Convolutional	256x3x3
Maximum	256x3x3
Convolutional	512x3x3
Maximum	512x3x3
Fully Connected	512
Fully Connected	256
Fully Connected	23

At the output, we have 23 neurons, because The alphabet consists of 13 letters and 10 numbers.

The method of training this network (as well as all the others in this work) is the method of back propagation of an error.

This algorithm corrects the weights of the neural network, allowing it to approximate the original function.

$$\delta^L = \nabla_a C \odot \sigma'(z^L) \quad (1)$$

$$\delta^l = ((w^l + 1)^T \delta^{l+1}) \odot \sigma'(z^l) \quad (2)$$

$$\frac{\partial C}{\partial b^l_j} = \delta^l_j \quad (3)$$

$$\frac{\partial C}{\partial w^l_{jk}} = a^{l-1}_k \delta^l_j \quad (4),$$

where $C$is the loss function; δ- error on the i-th layer; $\sigma(z)$- the output of the corresponding layer; a- network output to non-linearity; w, b- layer weights and their displacements, respectively

First, the total error at the network output is calculated. Then, according to formula (1), the correction factor of the corresponding layer is calculated. Further, the same factor is calculated for the remaining layers by formula (2). Formulas (3) and (4) serve to correct the corresponding layer weights and displacements.

The results of the system. On Fig. Figure 5 shows the correct operation of the implemented VS model.



Figure 5 - An example of the operation of the VS.

At stage 1, the borders of the license plate of the car are highlighted, then the picture is binarized, i.e. converted to black and white. Stage 3 serves to highlight the boundaries of each character. At the end of the work, the algorithm correctly recognizes each character of the license plate.

The accuracy of the algorithm for the test sample is 93%, and the time spent on recognizing one number is 4 seconds, which satisfies the specified quality criteria.

Chapter Conclusion *:* In this chapter, the implementation of the vision system of the parking robot was described. During the work, the following tasks were performed:

1) Choice of license plate recognition algorithm;
2) Choice of license plate detection methods;

3) Choice of methods of segmentation of characters on the automobile; room;
4) Choosing the architecture of neural networks to determine; license plate and classification of characters on it;

In the course of experiments with the system model, it was found that it correctly copes with the task.

1.7. Modeling the algorithm of the robot using the Petri net

For a visual description of the algorithm of operation and control of the parking robot, you can use the Petri net.

This Petri net uses the following notation:

- the circle indicates the state of the robot control system (indicated by the letter p with an index, for example, p1, p2, etc.);

- a segment denotes a transition, i.e. an action that must be performed to change the state of the control system (indicated by the letter t with an index, for example, t1, t2, etc.);

To describe the operation of the Petri net, the concept of "Chip" is introduced. A token is denoted by a dot inside the state, and the totality of all tokens in positions is called "Network Markup". The markup of the network determines the possibility of opening the corresponding transitions and changing the state of the system. The transition opens when the number of tokens in the corresponding states is greater than or equal to the number of arcs included in the transition. This network also uses inhibitor arcs. These arcs allow the transition to work only when there are no tokens in the position from which the arc originates.

The Petri net illustrating the operation of the robot is shown in Figure 1. This net is closed, which demonstrates the possibility of cyclic use of the control algorithm presented in it. To simulate the operation of the Petri net, a tree of achievable markings was compiled (Figure 2). When analyzing it, it should be noted that there are no dead-end branches, therefore, the freezing of the robot seems impossible

during normal operation. However, there are branches in the tree that lead to an infinite loop. These branches illustrate the situation of the robot getting stuck on its way, when the robot cannot skip or bypass the obstacle.

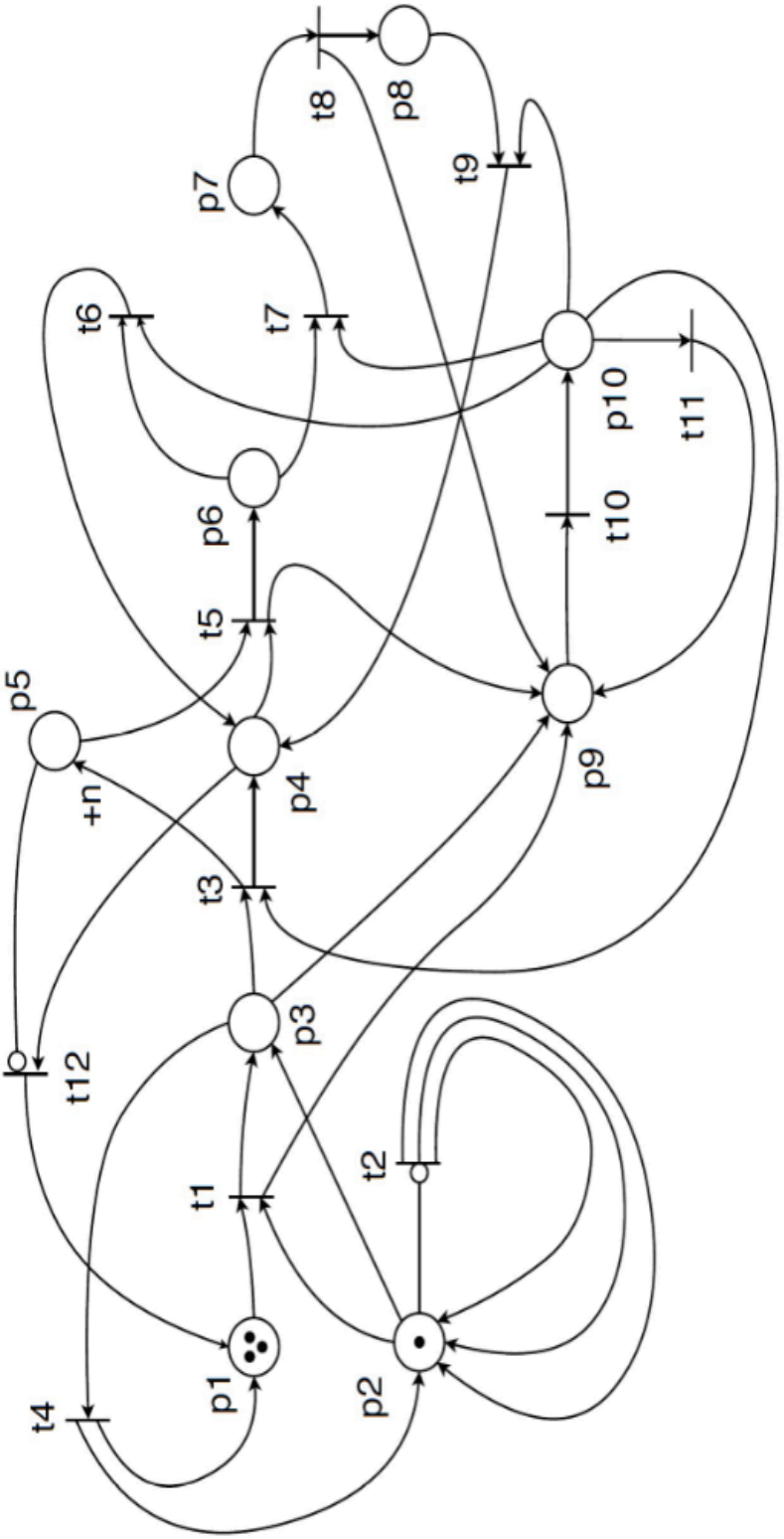


Figure 1 - Petri net

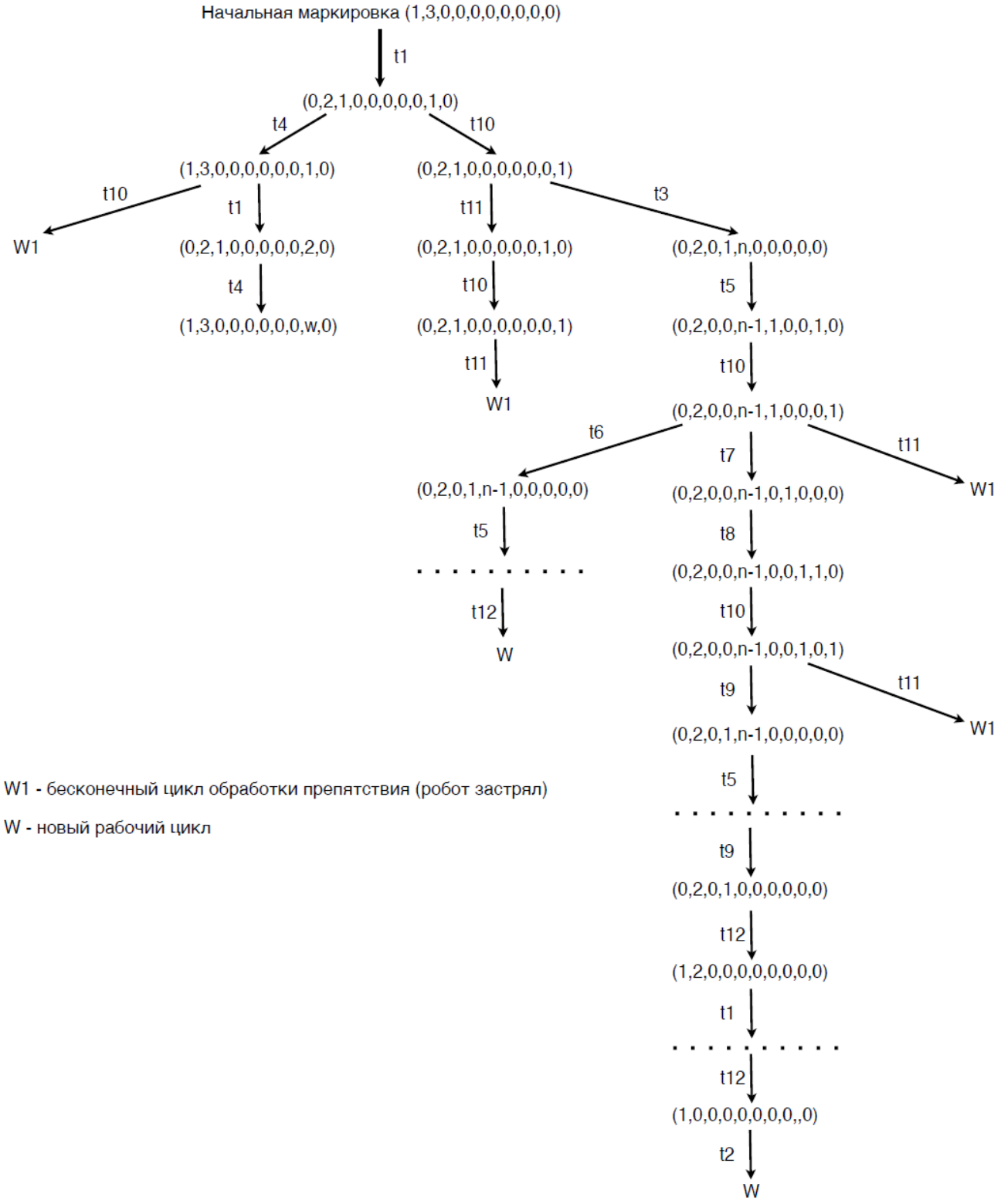


Figure 2 - Tree of Reachable Markings

The tree of reachable markings is compiled by sequential enumeration of all possible states of the system with the identification of infinite or dead-end branches in the logical operation of the RTK.

Description of network states and transitions:

p1 – robot at the charging station;

p2 - the battery is charged;

p3 – system diagnostics completed;

p4 – the robot entered the route;

p5 - it remains to inspect parking spaces;

p6 - the place was examined;

p7 – license plate recognized;

p8 - the machine is processed;

p9 - readiness of sensors for detecting obstacles;

p10 – data from sensors received;

t1 – carry out system diagnostics;

t2 - charge the batteries;

t3 - start moving;

t4 - report a breakdown (call a repair specialist);

t5 - inspect the next parking space;

t6 - drive further (the place was free);

t7 - stop and scan the license plate of the car (the place was occupied);

t8 – send license plate information to the server;

t9 - continue moving;

t10 - scan the space around the robot to detect obstacles;

t11 - work out the signal about the obstacle (stop and skip or
go around);

t12 - return to the charging station.

Description of the Petri net:

The initial state of the network corresponds to the following situation: the robot is at the charging station (p1), which is also the starting point of the route. We

consider that the battery charge of the robot (p2) is enough for several passages of the route, and the route can be different. Depending on the route, the number of parking spaces required for inspection (p5) may be different.

At the beginning of the working cycle, the robot needs to diagnose the health (t1) of its subsystems. If a malfunction is detected, the robot reports an error (t4) and is repaired, after which the work cycle can start over.

Before starting to move (t3, t6, t9), the robot needs to scan the surrounding area for obstacles, after which, in the absence of the latter, the robot can start moving. In this work, this is implemented only at the level of the algorithm. A case is possible when the robot loops along the path p9 - t10 - p10 - t11. This will mean that the robot is stuck or cannot handle the obstacle.

After the robot has entered the route (p4), it starts to inspect the parking spaces (t5). Further, 2 scenarios are possible: the inspected parking space (p6) turned out to be free, and the robot follows the route (t6), or the place was occupied by a car. In the latter case, the robot stops and scans the license plate of the car (t7), and after the number is recognized (p7), sends information about the license plate to the server (t8). Further, the parking space is considered processed, and the robot can continue moving along the route (t9).

When all the chips in position p5 are over, the route is considered completed, and the robot returns to its original position - the charging station (t12). If the chips in position p2 also run out, the transition t2 is triggered, signaling the battery charging procedure. After this procedure, the work cycle is repeated.

DESIGN PART

In the design part of this thesis, the selection of the necessary design of the drive for turning the video camera, the calculation of the thrust bearing of the camera, the calculation of the wheel shaft, the calculation of the wheel shaft bearings are made.

2.1. Chamber Thrust Bearing Calculation

Using the data obtained during the energy calculation of the chamber electric drive, we have that the radial force acting on the bearing is $F_r = 2$ N, and the axial force $F_a = 5$ N.

The static load condition has the following form:

$F_r \leq C_{0r}$ или $F_a \leq C_{0a}$,

where C_{0r} and C_{0a} are the static radial and axial load capacities of the bearing according to GOST 7872-89.

Based on the data presented in GOST, we find that any bearing from the light series is suitable for the camera rotation drive. Based on the fact that in the future the reasons from the camera, engine or other auxiliary devices can be removed into the camera stand, we select bearing 8105 (GOST 7872-89):

$d = 25$ мм, $D = 42$ мм, $B = 8$ мм, $r = 0,5$ мм, $C_a = 18000$ Н, $C_{0a} = 30000$ Н

Since the chamber rotation speed does not exceed 10 rpm, no dynamic load calculation is required. Let's take a look at durability.

Estimated durability is found by the formula:

$L_h = a_1 \bullet a_{23} \bullet \left(\frac{C_a}{P_a}\right)^p \bullet \frac{10^6}{60 \cdot n}$, Where

$a_1 = 1$- reliability coefficient, corrective resource depending on the required reliability;

$a_{23} = 0.75$- coefficient taking into account the design of the bearing and the conditions of its operation;

$p = 3$ для шарикоподшипников;

$n = 10$ об/минis the rotation speed of the inner ring;

P_a – equivalent axial load,

$P_a = F_a \bullet K_Б \bullet K_Т$,

Where

$K_Т$ – temperature coefficient, $K_Т = 1$for normal conditions;

$K_Б = 2$– coefficient taking into account the dynamics of loading;

$P_a = 5{\cdot}1 \bullet 2 = 10$ Н;

Then

$L_h = 1{\cdot}0.75{\cdot}\left(\frac{18000}{10}\right)^3 \bullet \frac{10^6}{60{\cdot}10} = 7,29{\cdot}10^{12}$часов$\gg$20000 часов.

This means that the condition of necessary durability is satisfied.

Static load test. Calculate the static safety factor

$S_0 = \frac{C_{0a}}{P_a} = \frac{30000}{10} = 3000.$

Static load verification is performed for any operating mode.

Based on the loading conditions and operation of the bearing, I choose the fit in the housing $\frac{JS7}{l0}$.

2.2. Wheel shaft calculation

To move the robot from its place, it is necessary to overcome the force of friction of the wheel on the asphalt. We accept with a margin the mass of the robot 100 kg. Then the friction force (on a dirt road) will be equal to

$F_{тр} = m{\cdot}g{\cdot}k_{тр} = 100{\cdot}10{\cdot}0.03 = 30$ Н;

$M_{кр} = 3.24$ Нм- torque;

$\sum M(3) = F_{тр} \bullet l_{31} + R_1 \bullet l_{32} = 0$;

$R_1 = \frac{F_{тр} \bullet l_{31}}{l_{32}} = \frac{30{\cdot}108}{52} = 62$ Н;

$$\sum F = \ -R_1 + F_{\text{тр}} - \ R_2 = 0;$$

$$|R_2| = |F_{\text{тр}} - R_1| = |30 - 32| = 32 \text{ Н}.$$

Let's build diagrams of forces and moments acting on the central shaft (Figure 1).

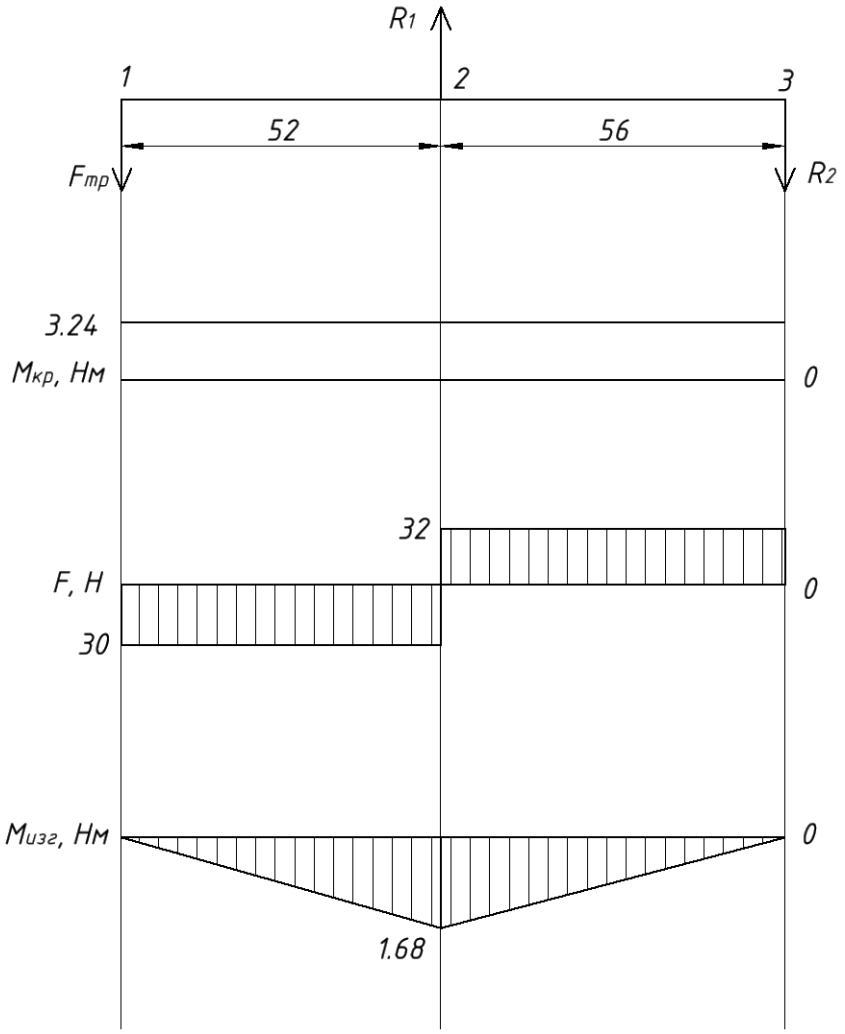


Figure 1 - Plot of forces and moments acting on the central shaft.

I accept the shaft material Aluminum D16T $[\sigma]_{\text{см}} = \ 75$ МПа.

I assign the diameter $d_2 = 25$ мм(bearing support No. 2) and the diameter $d_3 = 20$ мм(bearing support No. 3).

$M_{\text{изг}} = 1.68$ Нмis the maximum bending moment.

Since the loads on the shaft are quite small, it makes no sense to test it for suitability according to energy theory.

2.3. Calculation of wheel shaft bearings

$R_1 = 62$ Н, $R_2 = 32$ Н, режим нагружения 3.

Taking into account the loading mode, the radial forces are equal ($K_E$is the coefficient taking into account the loading mode)

$F_{r1} = K_E \bullet R_1 = 0.56 \cdot 62 = 34.7$ Н;

$F_{r2} = K_E \bullet R_2 = 0.56 \cdot 32 = 17.9$ Н.

Calculate the equivalent radial load:

$P_{rE1} = \left(x \cdot V \cdot F_{r1} + y \cdot F_{a1}\right) \bullet K_Б \bullet K_Т$;

$P_{rE2} = \left(x \cdot V \cdot F_{r2} + y \cdot F_{a2}\right) \bullet K_Б \bullet K_Т$.

In these formulas we have:

x, y – coefficients of radial and axial dynamic load;

$V$is the rotation coefficient;

because rotating inner ring$x = 1, y = 0, V = 1$;

F_{a1}, F_{a2}- axial forces. $F_{a1} = F_{a2} = 0$;

$K_Т$– temperature coefficient, $K_Т = 1$for normal conditions;

$K_Б = 2$– coefficient taking into account the dynamics of loading;

$P_{rE1} = (1 \cdot 1 \cdot 34.7) \bullet 2 \bullet 1 = 69.4$ Н;

$P_{rE2} = (1 \cdot 1 \cdot 17.9) \bullet 2 \bullet 1 = 35.8$ Н;

It turned out that 1 support is the most loaded, so further calculation is carried out for it.

I choose bearing 108105 GOST 8882-75:

$d = 25$ мм, $D = 47$ мм, $B = 12$ мм, $r = 1$ мм, $C_r = 11200$ Н, $C_{0r} = 5600$ Н,

and carry out for him checks for durability, static and dynamic load capacity.

Estimated durability is found by the formula:

$L_h = a_1 \bullet a_{23} \bullet \left(\frac{C_r}{P_{rE1}}\right)^p \bullet \frac{10^6}{60 \cdot n}$, Where

$a_1 = 1$- reliability coefficient, corrective resource depending on the required reliability;

$a_{23} = 0.75$- coefficient taking into account the design of the bearing and the conditions of its operation;

$p = 3$ для шарикоподшипников;

$n = 216$ об/мин– speed of rotation of the inner ring (we set the maximum speed of the robot to 10 km/h with a wheel radius of 123 mm);

$L_h = 1 \cdot 0.75 \cdot \left(\frac{11200}{69.4}\right)^3 \bullet \frac{10^6}{60 \cdot 216} = 2.43 \cdot 10^8$ часов $\gg$20000 часов.

This means that the condition of necessary durability is satisfied.

Dynamic load test:

$$C_{r\text{тр}} \geq P_{rE2} \sqrt[p]{\frac{60 \cdot L_{h\text{тр}} \cdot n}{a_1 \bullet a_{23} \bullet 10^6}};$$

$$C_{r\text{тр}} \geq 69.4 \sqrt[3]{\frac{60 \cdot 20000 \cdot 1440}{1 \cdot 0.75 \cdot 10^6}} = 916.6 \text{ Н}.$$

Received that $C_{r\text{тр}} = 11200 > C_r = 916.6$ - the condition is fulfilled.

Static load test. Calculate the static safety factor

$$S_0 = \frac{C_{0r}}{P_{rE1}} = \frac{5600}{69.4} = 80.7.$$

Static load verification is performed for any operating mode. Thus, the bearing pair is selected correctly.

For the second second support, we similarly select bearing 108104 (GOST 8338-75):

$d = 20$ мм, $D = 42$ мм, $B = 12$ мм, $r = 1$ мм, $C_r = 9360$ Н, $C_{0r} = 4500$ Н.

Bearing Fits:

Based on the loading conditions and operation of the bearings, I choose a fit on the shaft $\frac{L0}{js6}$.

Information on the wheel motor-reducer . For wheels, I also choose a Maxon engine, model EC 45 flat Ø42.9 mm, brushless, 30 Watt, with Hall sensors (Fig. 7.8).

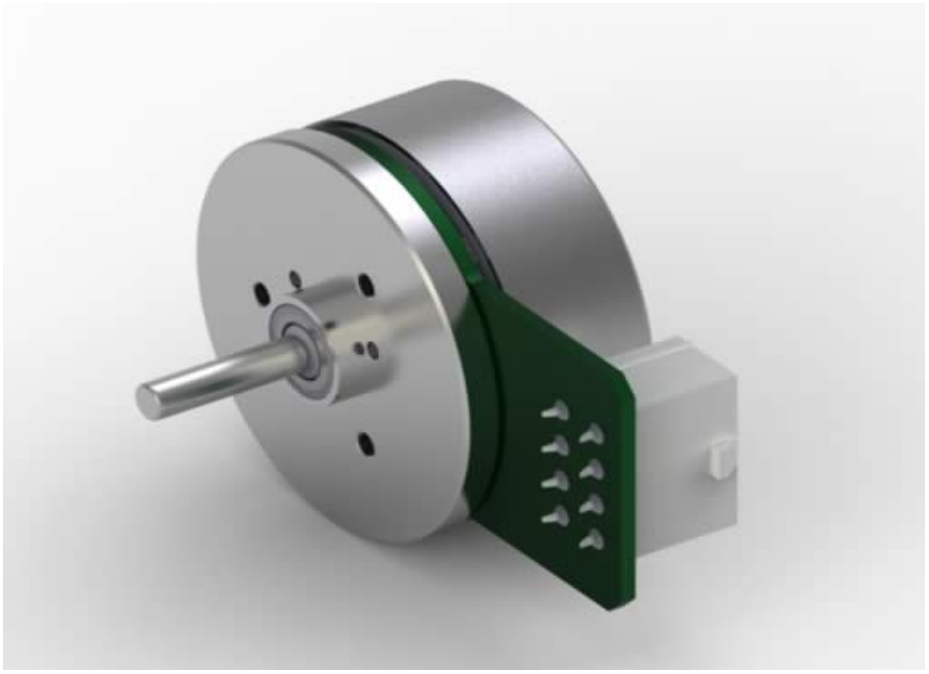


Figure 7 - Engine EC 45 flat Ø42.9 mm

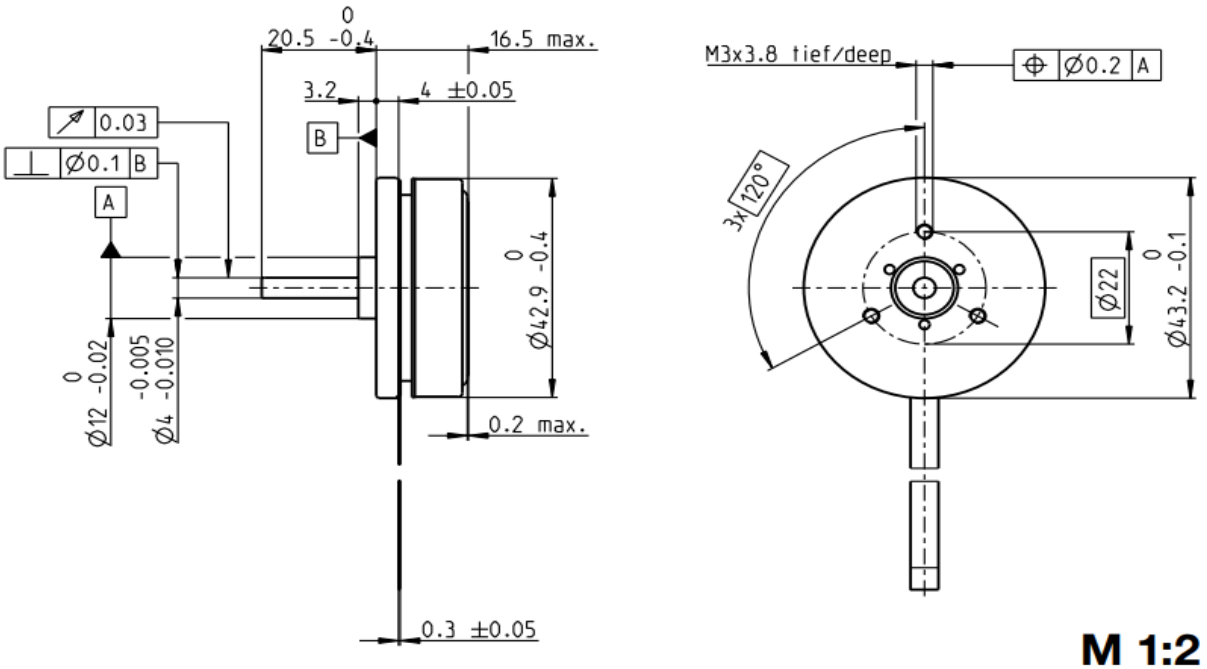


Figure 8 - Dimensional drawing of the engine

Table 5 - Main characteristics of the selected wheel motor

Rated voltage, V	24
Idling speed, rpm	6710
No-load current, mA	185
Rated speed, rpm	5240
Rated torque, mNm	83.4
Rated current, A	2.33
Starting torque, mNm	780
Starting current, A	23.3

To select a gearbox, it is necessary to determine how fast the robot will move. It is decided that the speed will be 10 km/h (2.78 m/s). Then the angular velocity of the wheel and, accordingly, the output shaft of the gearbox should be:

$$n = \frac{V}{2 \cdot \pi \cdot R},$$

where R is the radius of the wheel, R = 0.123 m, then

$$n = \frac{2.78}{2 \cdot \pi \cdot 0.123} = 3.6 \text{ об/с} = 216 \text{ об/мин}$$

Thus, the gear ratio of the gearbox should not be lower than

$$i = \frac{2910}{216} = 14.$$

I choose the Planetary Gearhead GP 42 C Ø42 mm, 3 - 15 Nm, Ceramic Version (Fig. 9.10).



Figure 9 - Planetary Gearhead GP 42 C

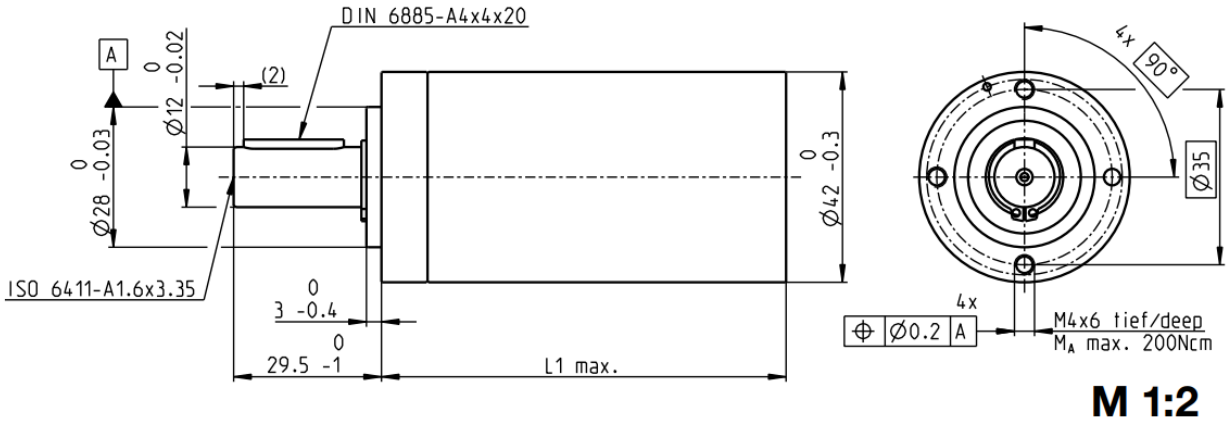


Figure 10 - Dimensional drawing of the gearbox

Table 2 - Main characteristics of the selected gearbox

Gear ratio	26:1
Number of steps	2
Maximum, continuously perceived moment, Nm	7.5
Maximum overload moment, Nm	11.3
Efficiency, %	81
Maximum radial load on the output shaft, N	240
Maximum input speed, rpm	8000

The kinematic diagram of the wheel drive is shown in Figure 11

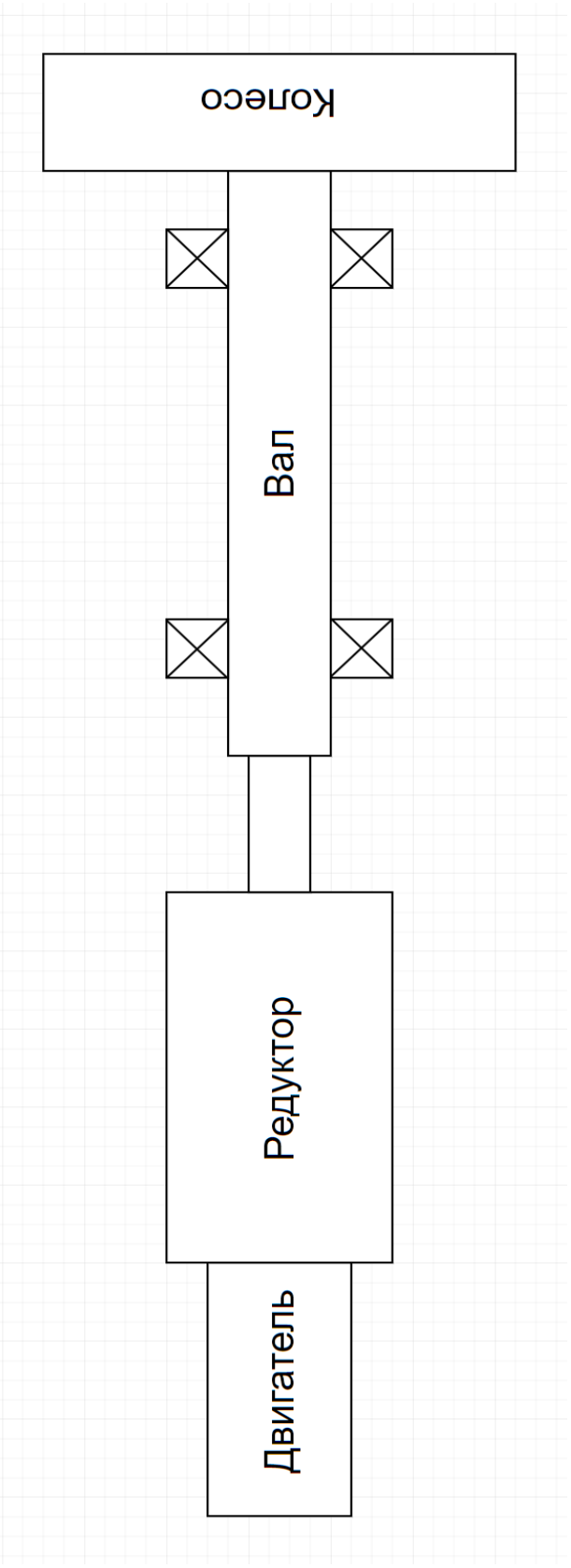


Figure 11 - Kinematic diagram of the wheel drive

CONCLUSION

In the course of the work, all tasks were completed.

The structure of the mobile robot control system was developed, and the components of the control system were selected.

A vision system was designed, the simulation of which showed its suitability for use within the framework of the task.

An algorithm for the operation of a mobile robot is determined, the correct operation of which is confirmed by the analysis of its operation using the Petri net.

The design of the video camera rotation unit has been developed, and the design of the units of the driving wheels of the robot has been presented. The execution of these nodes meets the set criteria for simplicity and ease of maintenance.

The simulation of the drive for turning the video camera was carried out. The analysis showed that this drive has a low overshoot index, which ensures the quality of the video camera positioning on the object, and also, given the small mass-inertia characteristics, it has an acceptable transient time, which should ensure a low processing speed of an individual vehicle, and, consequently, high performance the efficiency of the route as a whole.

Thus, the developed mobile robot is able to perform all the tasks assigned to it, and the quality of its work meets the requirements.

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APPENDIX A

List of graphic (illustrative) material (drawings, posters, slides, etc.)

1 sheet (A1) - Drawing of the camera rotation module ;

2 sheet (A1) - Assembly drawing of the drive design.