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TECHNICAL SCIENCES

A SMALL-SCALE MANIPULATION ROBOT A LABORATORY LAYOUT DEVELOPMENT

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Abstract

This article is devoted to the control system development for a mobile manipulation robot with a computer vision system. A feature of this study is the development of a decentralized control system based on microcontroller modules with the possibility of remote control using wireless networks. During the design, the authors developed a generalized block diagram of the manipulation robot and analyzed and selected hardware modules for implementing the control system. For the implementation of the laboratory layout of a mobile manipulation robot, the restrictions that are imposed on the control system were selected and justified. Based on these restrictions, it was proposed to use the following hardware modules: ESP32-Cam - for computer vision system implementation and ESP32 Devkitc v4 for motion control system implementation 2WD robotic platform and control system for the manipulator itself. Based on the selected hardware modules, a block diagram of the information interaction of the main modules of a mobile manipulation robot and an electrical circuit diagram are proposed, an experimental model of a small-sized manipulation robot is assembled to test the control system. A generalized control algorithm for a mobile manipulation robot has been developed based on the "client-server" architecture approach using "thin client" technologies, which makes it possible to use any mobile device that supports hardware connection to Wi-FI and any Web browser.

***Keywords**: mobile robots, mobile manipulation robots, control systems, computer vision system, decentralized control system, laboratory layout*

Introduction

The modern development of robotics, which has led to the introduction of new technologies within Industry 5.0, poses new challenges for the development of mobile small-sized manipulation robots that allow not only to analyze the environment, but also to influence it with the help of a manipulator [1,2]. These small-sized mobile robots can be used in areas of man-made disasters, in the study of narrow enclosed spaces that occur during the collapse of reinforced concrete structures [3,4]. Small size and mobility allows the manipulation robot to penetrate narrow passages between structural elements and analyze the environment and transmit data to the operator. As a result of this, the task of developing this robot using small hardware modules based on microcontroller technologies arises. This will allow not only to implement a platform and manipulator control system, but also to implement a computer vision system with the ability to further use it as a system for identifying and recognizing objects on the basis of artificial intelligence (AI), which will simplify the work of the operator [5,6].

Literature Analysis

Zhengxue Zhou's work gives an example of a mobile robotic arm with a computer vision system development. The mobile robotic arm is equipped with cameras, an in-house developed adaptive grip, and a computer vision training system based on the PV-RCNN network model [7]. The developed robot is attracted to automatic production processes in small and medium-sized enterprises (SMEs), as a result of which it has significant dimensions and high requirements for hardware modules, for example, for the operation of a neural network, this robot uses a GEFORCE RTX 3090 GPU, and therefore this robot cannot be considered small-sized. An article by Dmitry Topolsky gives an example of the experience of developing a mobile robot for Mine Exploration, the mobile robot control system is built on the basis of a Raspberry Pi 3 single-board computer using the Multi Camera Board V.2.1 module, which makes it possible to connect two Rpi Camera cameras for visualization of the surrounding space [8]. The developed prototype has a number of limitations of the working environment, such as the minimum height and width should not be less than 300mm, which is due to its overall dimensions, while the mobile robot does not have a manipulator, which limits its functionality. In [9], the authors presented an approach to designing equipment and a control system for a mobile manipulation platform that was used in the MBZIRC 2020 competition. The mobile robot is controlled based on OS ROS, and the video stream is processed based on the Open CV library. The mobile platform is equipped with a manipulator, which makes it possible to move small objects. For visualization of the surrounding space, the authors use RS-LiDAR16 and the Intel Realsense D435 camera, which leads to an increase in the overall dimensions of the mobile manipulation platform and does not allow its use in confined spaces. As you can see, research in the development of mobile manipulation platforms is an urgent task, especially creating prototypes for working in confined spaces in areas of man-made disasters.

Setting the Research Goal

The main goal of this study is to develop a decentralized control system for a small-sized mobile manipulation robot with the function of visualizing the environment through a computer vision system.

Разработка макета малогоборитного манипуляционного робота

A Small-Sized Manipulation Robot Layout Development

At the first stage of a small-sized manipulation robot laboratory layout development, it is necessary to design a block diagram, determine the main elements and the type of relationships between them. As a result, it is necessary to define a number of restrictions that will be imposed both on the entire structure and on individual hardware modules, as well as on the proposed design solutions. Based on the purpose of the development, it is proposed to present a block diagram in the form of a set of block elements and the relationship between them. We define the following main blocks for the implementation of a small-sized mobile manipulation robot:

- Computer Vision System (CVS) module for processing and broadcasting a video stream, via wireless networks, for visualizing the environment to the operator;
- Sensor (S) sensors for sensing the mobile robot (ultrasonic, infrared);
- Manipulator Control System (MCS) manipulator control system (servomotors);
- Engine Management System (EMS) motor control system (DC Motor), to ensure the movement of the mobile platform.
- Robot Control System (RCS) a system for controlling the movement of a mobile platform and processing data from sensors on which the manipulator is installed;
- Power Management System (PMS) power management of the mobile robot and manipulator;
- Motor (M) propellers (motors).

The developed generalized block diagram of the developed manipulation robot is shown in Figure 1.

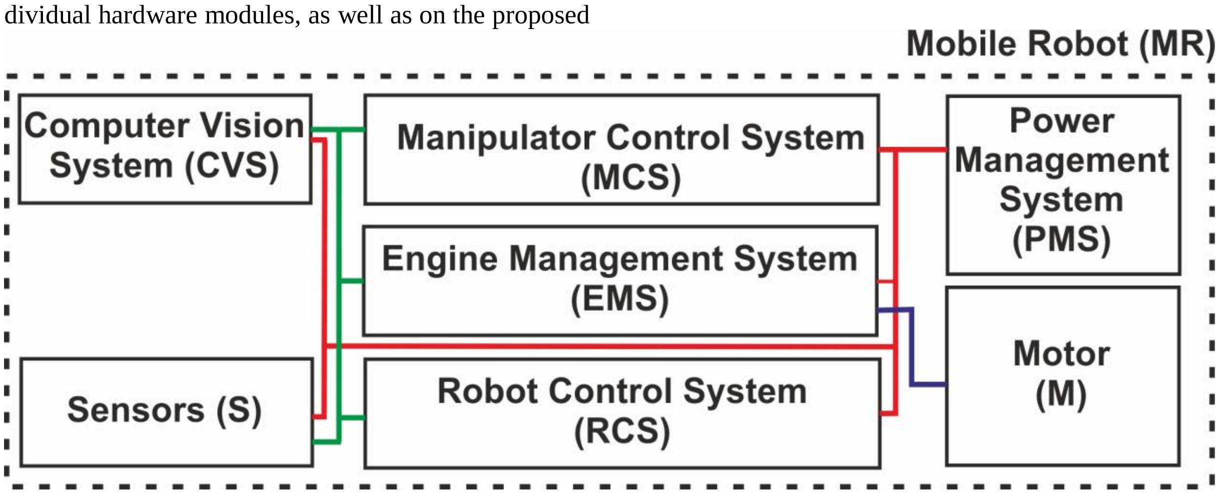


Figure 1. – Generalized Block Diagram of the Developed Manipulation Robot

The next step in the development of a small-sized manipulative robot is to analyze, determine the restrictions and select hardware modules on the basis of which the developed block diagram can be implemented (Fig. 1.).

To implement the functions of the Computer Vision System (CVS), it is necessary to select a microprocessor module with the ability to connect and work with a video camera. Let's define the range of some restrictions that must be taken into account during development:

- overall dimensions no more (~40.5*27*5mm);
- supply voltage (no more than 5V);
- matrix resolution SVGA 800x600 (30 fps)
- the ability to transmit streaming video via wireless networks;

In the course of the analysis of existing hardware modules that satisfy the identified restrictions, are presented in Figure 2, and a comparison of their parameters is presented in Table 1

a) b) c)

a) ESP32-Cam Wi-Fi Bluetooth, камера OV2640 [10]
b) Miniature TTL Serial JPEG Camera with NTSC Video [11]
c) OpenMV Cam M7 Open Source Computer Vision Board [12]
Figure 2 – Microprocessor Modules for Computer Vision System Implementation

As you can see from Table 1, the Miniature TTL Serial JPEG Camera module is not suitable as a CVS, since you need to buy an additional microcontroller-based module, the remaining two ESP32-Cam and OpenMV Cam M7 modules have similar parameters, but have a difference in the development environment. To develop the ESP32-Cam firmware, the Arduimo IDE based on the C++ language is used, OpenMV Cam M7 recommends the MicroPython language, as a result of which it is proposed to use ESP32-Cam to develop the CVS of the experimental layout, since it has smaller overall dimensions and is also acceptable in terms of price.

The next step is to select the Manipulator Control System (MCS) as well as the Robot Control System (RCS). Let's define the basic requirements for these modules:

- not large overall dimensions;
- the ability to connect additional modules;
- support for wireless networks.

Table 1 – - Computer Vision System Hardware Modules Main Characteristics Comparison

Parameters	Hardware Modules		
	ESP32-Cam Wi-Fi Bluetooth, camera OV2640 [10]	Miniature TTL Serial JPEG Camera [11]	OpenMV Cam M7 [12]
MCU	32-bit dual-core microprocessor Xtensa	-	STMicro STM32F765VI ARM Cortex M7
Operating frequency (MHz)	до 240	-	216
Memory	512KB RAM, 4 MB flash + micro SD slot	-	512KB RAM, 2 MB flash + micro SD slot
Camera	OV2640, OV7670	OV2640	Omnivision OV7725
Image size	UXGA 1600x1200 (15 fps) / SVGA 800x600 (30 fps)	VGA（640*480), QVGA（320*240), QQVGA（160*120）	640×480 8-bit grayscale images or 320×240 16-bit RGB565 images at 30 FPS
Viewing angle	70-120	90	70
Wireless Module	WiFi 802.11 b/g/n + Bluetooth 4.2 LE	-	WiFi 802.11 b/g/n + Bluetooth 4.2 LE
Power Supply (V)	5	5	5
Power Consumption (V)	3.3	3.3	3.3
Dimensions (mm)	27*45*40	20*28	45*36*30
Weight (g)	8	3	16
Цена	~10$	~35$	~64$

Let's analyze the hardware modules that can be used for Manipulator Control System (MCS) and Robot Control System (RCS) implementations. The selected modules are shown in Figure 3, and their technical characteristics are in Table 2.

a) *b)* *c)*

a) ESP32 Devkitc v4 [13]
b) WI-FI модуль WeMos D1 mini [14]
c) Wi-Fi модуль ESP8266 Witty Cloud [15]
Figure 3 – Microprocessor Modules for MCS and RCS Implementation

Table 2

Comparison of the Hardware Modules Main Characteristics for Implementation Manipulator Control System (MCS) and Robot Control System (RCS)

Parameters	Hardware Modules		
	ESP32 Devkitc v4 [13]	WI-FI module WeMos D1 mini [14]	Wi-Fi module ESP8266 Witty Cloud [15]
MCU	2-core 32-bit processor Tensilica Xtensa LX6	32-bit processor	32-bit processor
Operating frequency (MHz)	до 240	80	160
Memory	512KB RAM, 4 MB flash + micro SD slot	512KB RAM, 4 MB flash	512KB RAM, 4 MB flash
Wireless Module	Wi Fi 802.11 b/g/n + Blue-tooth 4.2 LE	Wi Fi 802.11 b/g/n	Wi Fi 802.11 b/g/n
Hardware Interfaces	3×UART;3×SPI; 2×I²C; 3× I²S	SPI, I2C, I2S, 1-wire, UART, UART1, IR Remote Control	UART, HSPI, I2C, I2S
Power Supply (V)	5	5	5
Power Consumption (V)	3.3	3.3	3.3
Dimensions (mm)	48*27*5	33*26*6	30*30*20
Weight (g)	15	10	18
Price	~5-7$	~5-6$	~4-6$

Based on the results of the comparison, we can single out the ESP32 Devkitc v4 module, since it has a large number of supported interfaces, with which you can implement the connection of additional hardware modules and sensors to feel the mobile manipulation platform, this module will also allow you to develop a decentralized approach to management manipulation robot by dividing tasks: ESP32-Cam will implement the functions of the Computer Vision System, and ESP32 Devkitc v4 will be responsible for working with the manipulator and the mobile robot platform movement system.

For the Engine Management System (EMS) implementation - motion control of a mobile manipulation platform, a 2WD platform based on DC Motor with the following parameters was chosen: voltage 3-6V; current 180-500mA; moment 0.7 kg/cm. Based on the above parameters, it is proposed to use the following hardware modules for DC Motor control, which are shown in Figure 4, and their technical characteristics in Table 3.

a) b) c)

a) motor driver L298N [16]
b) motor driver L9110S[17]
c) motor driver MX1508 [18]
Figure 4 – Motor Driver Hardware Modules

Table 3

Motor Driver Hardware Modules Main Features Comparison

Parameters	Motor Driver		
	L298N [16]	L9110S [17]	MX1508 [18]
Module Supply Voltage	3-35B	2.5-12 B	2-10 B
Input Voltage	5-7 B	1.8-7 B	1.8-7 B
Operating Current	operating 2 A, peak 3 A	operating 1.5 A, peak 2.5 A	operating 1.5 A, peak 2.5 A
Cooling System	+	-	-
Dimensions (mm)	44*44*27	30*23*15	25*21*0.75
Weight (g)	26	6	4
Price	~2$	~1,5$	~1$

Analyzing the comparison of the main characteristics of motor drivers, we can distinguish two groups: the first is modules based on L9110S and MX1508, and the L298N module. The L298N module is designed to control more powerful motors, and therefore has passive cooling and is more reliable than analogues. Based on the characteristics of the selected hardware modules, the following block diagram of the information interaction of the main modules of the mobile manipulation robot is proposed, which is shown in Figure 5.

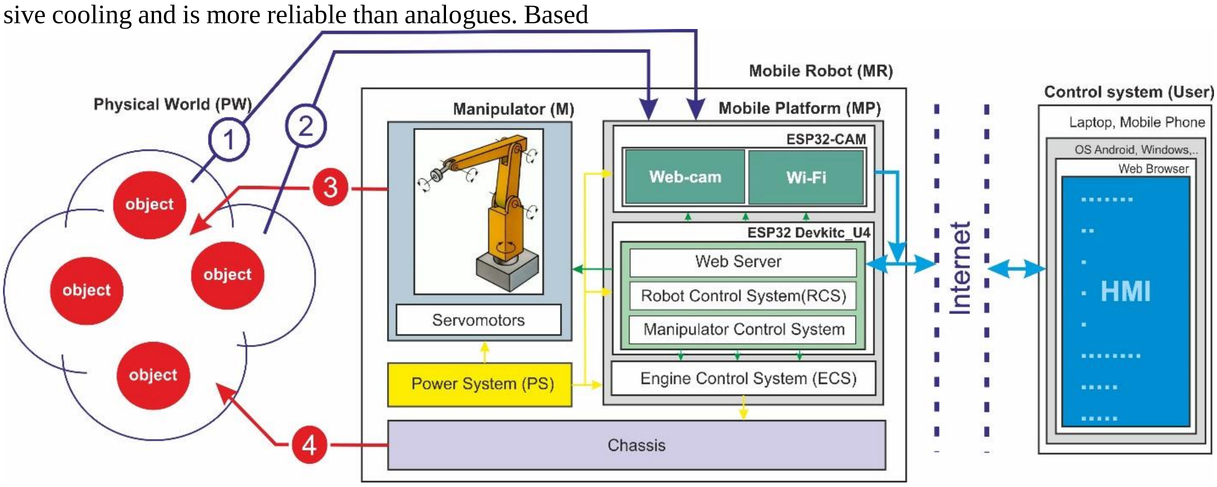


Figure 5 – Structural Diagram of the Information Interaction between the Main Modules of a Mobile Manipulation Robot

The mobile platform (MP) hosts two hardware modules ESP32_Devkite_U4 and ESP32-CAM. ESP32-CAM implements a computer vision system via wireless data transmission technology to the operator by creating a local Web service with the ability to broadcast streaming video. An access point is created on the ESP32_Devkite_U4 board, to which an asynchronous Web server is connected, which is designed to control the movement of the robotic platform, as well as to control the manipulator itself. The rationale for this decision was an attempt to distribute the level of loads on the hardware modules, since they do not have high speed, which accordingly increases the reaction time of the mobile manipulation robot to the operator's commands. The proposed solution will significantly increase the speed of processing commands and reduce their execution time. The interaction of a mobile manipulation robot with the surrounding physical world ("object") occurs due to the influence on it through the manipulator (Fig. 2. designation 3) and the Chassis module, which ensures its movement in space (Fig. 2. designation 4). Obtaining data on the environment is carried out through a Web camera (Fig. 2. designation 1) and an ultrasonic sensor (Fig. 2. designation 2). The control of a mobile manipulation robot is carried out by the operator through a portable device (Laptop, Mobile Phone). The main requirement for a mobile robot control system is the presence of a Wi-Fi hardware module and a Web browser.

The next step in the development of a laboratory layout of a manipulation robot is the design of an electrical circuit diagram in the Altium Designer 20.2 PCB environment using the specifications of the selected hardware modules [19]. The developed electrical circuit diagram is shown in Figure 6. 3 batteries of the 18650 serie (3.7V, 3500mA) will act as batteries, to control the power supply of the ESP32-Cam, ESP32_Devkite_U4 modules will be carried out through the DC Converter LM2596S, which will reduce the input voltage from 12V to 5V [20].

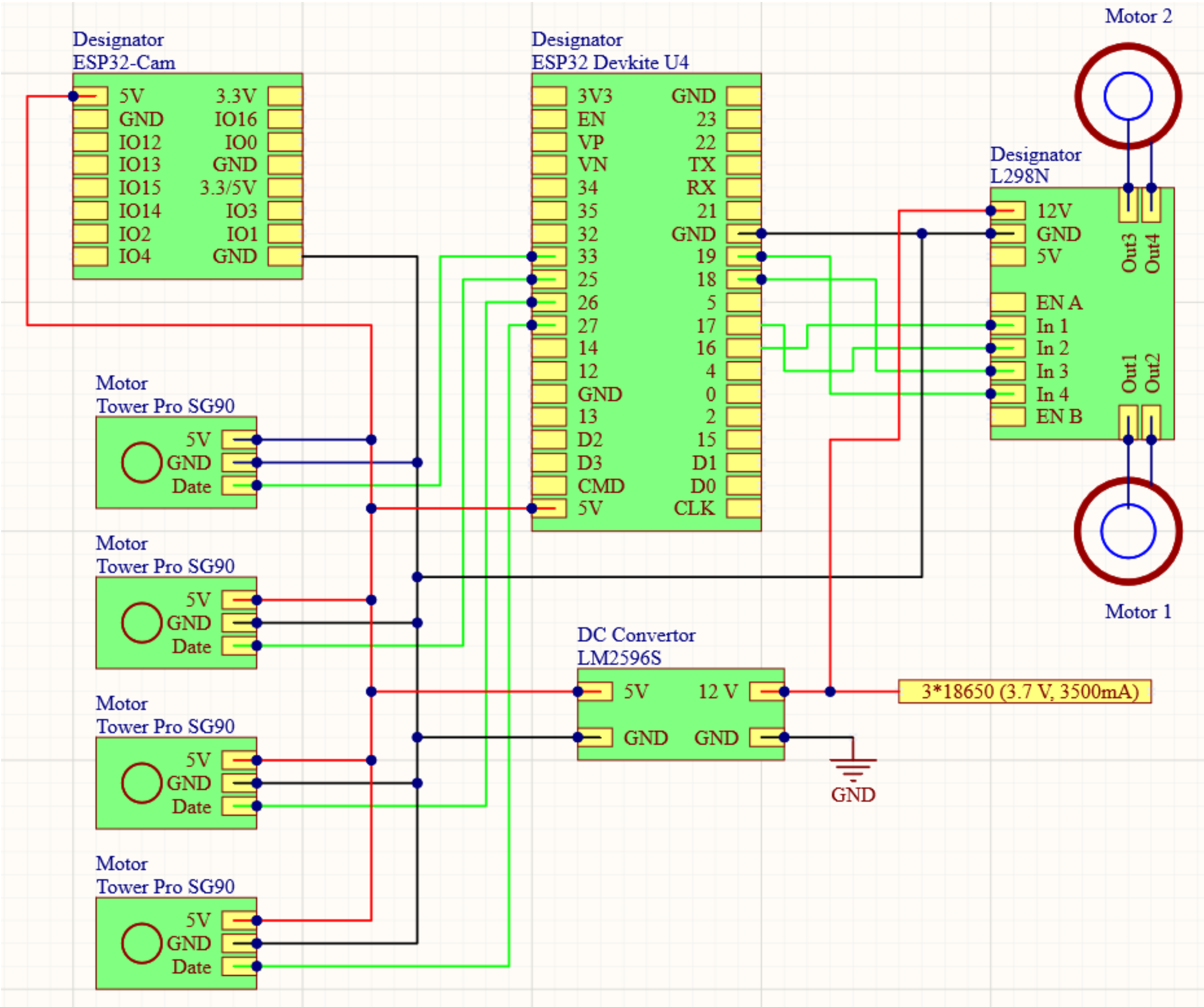
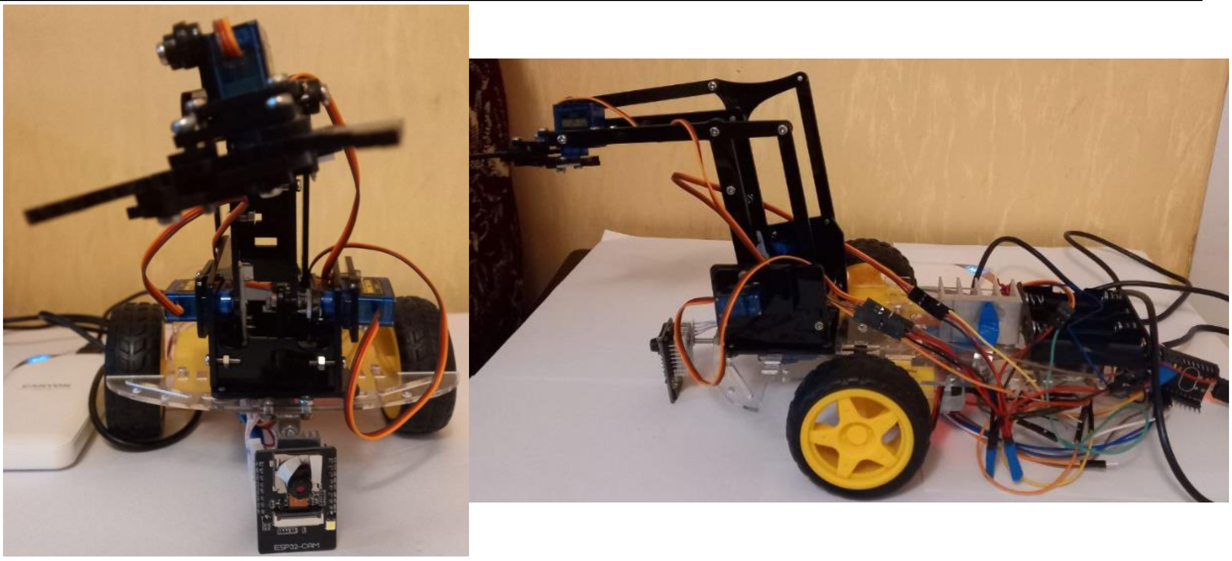


Figure 6. – Electrical Circuit Diagram

Based on the developed electrical circuit diagram, a laboratory layout of a mobile robot with a manipulator was assembled on the basis of the Arduino 2WD platform chassis [21]. The assembled layout is shown in Figure 7.

In the future, the platform can be replaced, depending on the tasks that are set for the mobile manipulation robot, both for wheeled (4WD) and caterpillar ones with more powerful engines, while the developed control system and computer vision system do not change.



a) b)

a) front view
b) side view
Figure 7. – Laboratory Layout of a Mobile Robot with a Manipulator

Development of an algorithm and program for the control system of a mobile robot with a manipulator

To work out the control mechanisms and operation of the computer vision system of the developed laboratory layout, it is necessary to develop a software package that will enable the operator to solve the set manipulation tasks with objects. At the initial stage, we will develop a generalized algorithm for control systems for a mobile manipulation robot, which is shown in Figure 8.

As can be seen from Fig. 8, the general control algorithm of a mobile robot, the control system of a manipulating robot is presented in the form of two independent algorithms, both a mobile manipulative robot and an operator of a mobile robot [22-30]. Let's describe the main elements of the Mobile Manipulation Robot algorithm:

1. Library initialization – initialization of libraries for working with ESP32-Cam and ESP32_Devkite_U4 (esp_camera.h, WiFi.h, Arduino.h, sp_http_server.h, etc.) which will make it possible to implement all the basic functions;

2. LAN Connections – connecting hardware modules to a local wireless network (Wi-Fi);

3. Starting the Web Server – initialization and launch of the Web Server based on ESP32-Cam and ESP32_Devkite_U4;

4. Camera Initialization – initialize and start streaming video from the camera ESP32-Cam;

5. Robot Control HMI Initialization – mobile platform motion control interface initialization;

6. Initialization the HMI Control of the Manipulator – initialization of the manipulator control interface;

7. Timer Counter – time counter, to update waiting for operator commands in time;

8. Waiting for Commands from the Operator – the procedure for waiting for commands from the operator by a mobile manipulation robot.

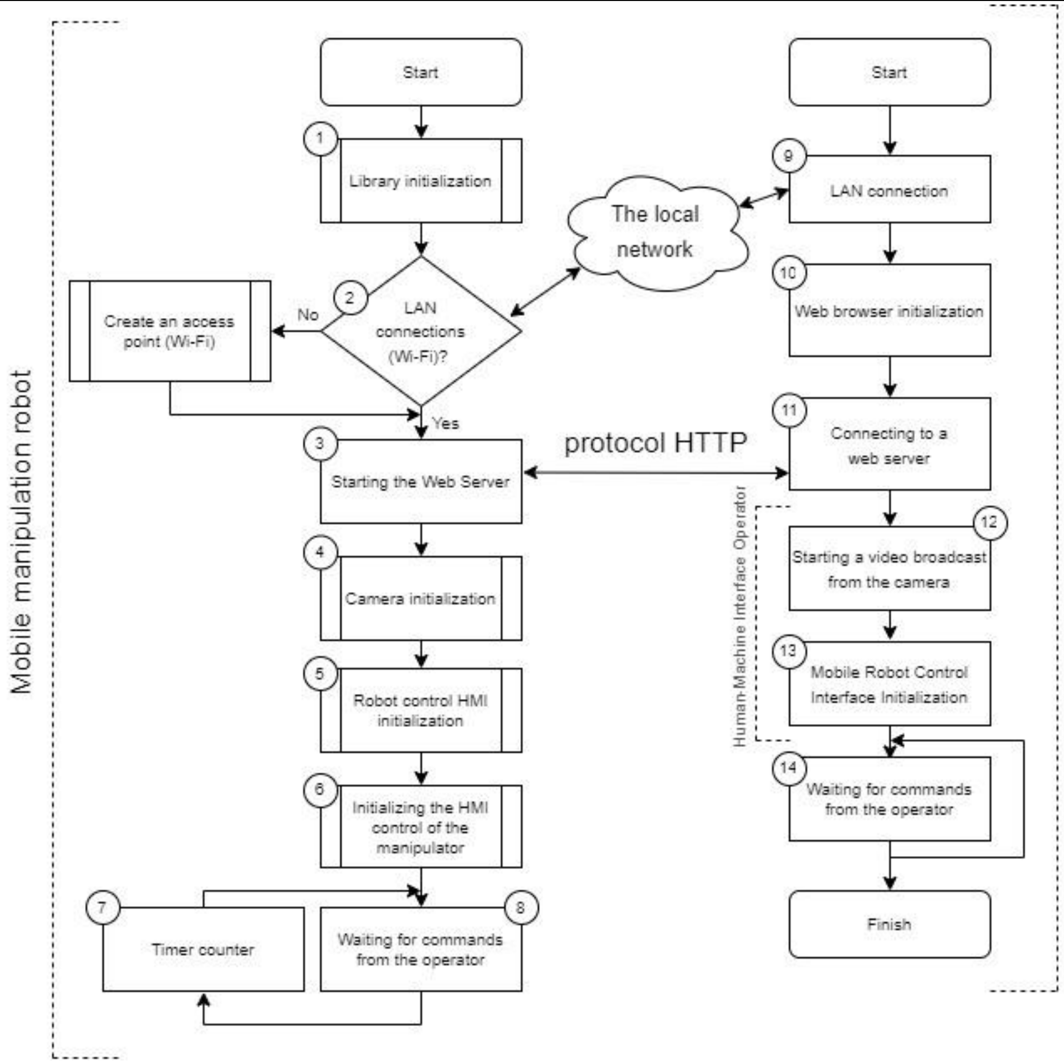


Figure 8. – Generalized Control Algorithm for a Mobile Manipulative Robot

Key elements of the Operator`s Mobile Device algorithm:

9. LAN Connections – wireless LAN connection functions;
10. Web Browser Initialization – initialization of the Web Browser installed on the mobile device of the operator;
11. Connecting to a Web Server – setting up a connection to the Web Server on the ESP32-Cam and ESP32_Devkite_U4 modules within a single HMI;
12. Starting a Video Broadcast – launching the functions of displaying the video stream in the operator's HMI;
13. Mobile Robot Control Interface Initialization – initialization and display of control commands for a mobile robot and a manipulator;
14. Waiting for Commands from the Operator – procedure for waiting for commands from the operator.

Data transfer between the mobile manipulation robot and the operator control device is based on the concepts of a "thin client" client-server architecture, based on the HTTP protocol. That will allow you not to install additional software on the operator's mobile device.

Here is a description of the implementation of some functions for the computer vision system in the Arduino IDE.

The initialization of the CameraServer for streaming video via the HTTP protocol via port 80, using the GET method, is presented below.

```
void startCameraServer(){
httpd_config_t config = HTTPD_DEFAULT_CONFIG();
config.server_port = 80;
httpd_uri_t index_uri = {
.uri = "/",
.method = HTTP_GET,
.handler = stream_handler,
.user_ctx = NULL
```

To test the launch of the OV2640 camera module on the ESP 32-Cam, it is proposed to use the following function, with the ability to output an error code to the Arduino IDE port monitor.

```
esp_err_t err = esp_camera_init(&config);
if (err != ESP_OK) {
Serial.printf("Camera init failed with error 0x%x", err);
return;
```

Connecting the ESP32-Cam module to a local wireless network is implemented in the following way-

```
WiFi.begin(ssid, password);
while (WiFi.status() != WL_CONNECTED) {
delay(500);
Serial.print(".");
```

```
}
Serial.println("");
Serial.println("WiFi connected");
Serial.print("Camera Stream Ready! Go to: http://");
Serial.print(WiFi.localIP());
```

The movement control of the mobile platform and the control of the onboard manipulator are implemented on the basis of the module, an example of the implementation of the commands for moving the mobile platform when executing the "Forward" command is presented below.

```
if(key == "Forward") {
 Serial.println("Forward");
 digitalWrite(MOTOR_1_PIN_1, 0);
 digitalWrite(MOTOR_1_PIN_2, 1);
 digitalWrite(MOTOR_2_PIN_1, 0);
 digitalWrite(MOTOR_2_PIN_2, 1);
```

Similar to the "Forward" command, the following commands are executed: "Left", "Stop", "Right", "Backward".

The initial position of the servomotors of the mobile manipulator for each link will be set as a ServoPins vector with specified rotation angles, as the initial points of the report:

```
std::vector<ServoPins> servoPins =
{
 { Servo(), 27 , "Base", 90},
 { Servo(), 26 , "Shoulder", 90},
 { Servo(), 25 , "Elbow", 90},
 { Servo(), 33 , "Gripper", 90},
};
```

To visualize the control menu of the "Gripper" command by the robot manipulator for the operator, in HTML, we will describe the following block element inside which the range visual element is located, with the parameters of the minimum and maximum angle.

```
<div class="slidecontainer">
 <input type="range" min="0" max="180" value="90" class="slider" id="Gripper" oninput='sendButtonInput("Gripper",value)'>
 </div>
```

The developed control interface for a mobile manipulation robot with a computer vision system is shown in Figure 9.

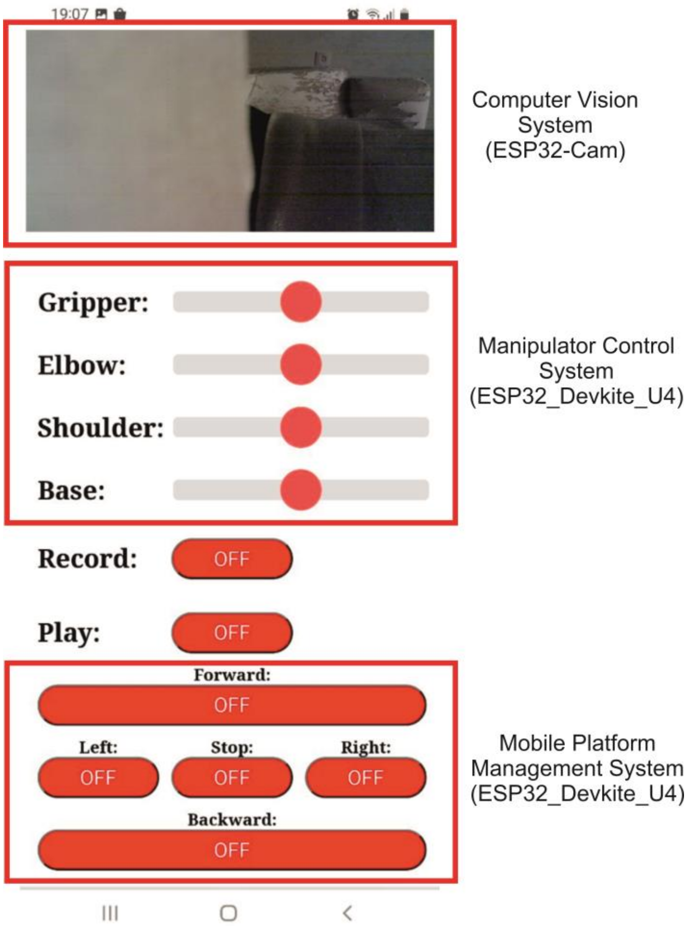


Figure 9. – Control Interface for a Mobile Manipulation Robot with a Computer Vision System

As can be seen from Figure 9, the mobile manipulation robot control interface is divided into three main control blocks, the Computer Vision System block transmits streaming video from the ESP32-Cam hardware module with SVGA 800x600 resolution (30 fps). The Manipulator Control System block allows you to implement the control of the position of the links and the capture of the manipulator in manual mode. The Mobile Platform Management System block makes it possible to control the movement of a 2WD mobile platform. Additional buttons "Record" allows you to record a video stream on the control device for further analysis by the operator for a more detailed assessment of operating situations.

Conclusions

In the course of the research on the development of a mobile small-sized manipulation robot, the authors developed a generalized block diagram. Taking into account the peculiarities of the application and restrictions on the requirements for overall dimensions, it was proposed to use a decentralized control system, in the form of separate hardware modules based on microcontrollers. This solution makes it possible to separate the computer vision system and the control system of the mobile platform and the manipulator, which improves performance. The analysis of modules for the implementation of control systems and computer vision systems was carried out, showed that within the framework of these studies, the ESP32-Cam and ESP32_Devkite_U4 modules are suitable, which fully meet the requirements for small-sized mobile manipulation robots. Based on this, an electrical circuit diagram of a mobile robot was designed and a laboratory model was assembled to verify the correctness of the development of a decentralized control system. The software implementation of the control system is built on the basis of the "client-server" architecture on the "thin client" method using the Web Server approach. The Web Server view will use the ESP32-Cam and ESP32_Devkite_U4 hardware modules to solve certain problems. We will develop a generalized algorithm for control systems for a mobile manipulation robot and provide fragments of functions for implementing streaming video transmission from the ESP32-Cam module and functions for processing commands for moving the mobile robot platform and controlling the manipulator itself based on the ESP32_Devkite_U4 module. A feature of the developed decentralized control system is that no additional software needs to be installed on the operator's mobile device and the control system is a cross-platform solution. In the future, the authors plan to redesign the design of a small-sized mobile manipulation robot, optimize the placement of components, develop a new design in the CAD system and use a 3D printer. And to integrate the Yolo v.4 library into the computer vision system, which in the future will allow for the identification of objects in the working area of the mobile robot.

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